Development and Application of Taiwan Earthquake Loss Estimation System (TELES) in Highway Bridges

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ABSTRACT

After Chi-Chi Earthquake struck Taiwan on September 21, 1999, Taiwan Area National Freeway Bureau (TANFB) actively took preventive measures for bridges that were opened to traffic. Based on the seismic vulnerability rating results and prioritization studied by using the Taiwan Earthquake Loss Estimation System (TELES), Taiwan freeway bridge authority initiated a three-phase seismic retrofit program in 2000. This paper reports the overall program scope, seismic evaluation criteria, retrofit method, budget and schedule. The information is valuable for engineers and stakeholders from managing system perspective.

The National Science Council of Taiwan started HAZ-Taiwan project in 1998 to promote researches on seismic hazard analysis, structural damage assessment, and socio-economic loss estimation. The associated application software, “Taiwan Earthquake Loss Estimation System (TELES)”, integrates various inventory data and analysis modules to fulfill three objectives. First, it helps to obtain reliable estimates of seismic hazards and losses soon after occurrence of large earthquakes. Second, it helps to simulate earthquake scenarios and to provide useful estimates for local governments or public services to propose their seismic disaster mitigation plans. Third, it helps to provide catastrophic risk management tools, such as proposing the seismic insurance policy for residential buildings.

This paper also proposes the preliminary integration framework of TELES and T-BMS. The Taiwan Bridge Management System (T-BMS) was initially developed in 1999 and has been set online since 2000. Funded by the Institute of Transportation under the Ministry of Transportation and Communications, the T-BMS is a web-based system widely used by all of the bridge management agencies in Taiwan. It has been a useful tool in bridge management and maintenance. Bridge data are readily accessible to. The latest version consists of eight functional modules: (1) Inventory; (2) Inspection; (3) Maintenance; (4) Statistics; (5) Decision Support; (6) Geographical Information System; (7) Precursory; and (8) Parameters Setting.

With an inventory of more than 29,000 bridges in T-BMS, the efficient data integration of TELES and T-BMS will help all bridge authority to plan and stimulate efforts to reduce risk and to prepare for emergency response and recovery from a future catastrophic earthquake.

Keywords: Seismic Retrofit; Prioritization; TELES; T-BMS, Damper; Steel Jacketing; Concrete Jacketing; SafeTaiwan; IoT.

1. INTRODUCTION

Chi-Chi Earthquake measuring 7.3 on the Richter scale struck Taiwan on September 21, 1999, as shown in Figure 1. The devastating event caused severe property losses and casualties to central Taiwan. Since earthquakes are unpredictable, they often cause more severe disasters if they are not treated cautiously. Taiwan Area National Freeway Bureau (TANFB) took proactive actions towards those bridge structures that were designed, constructed and opened to public before December 31, 2000.

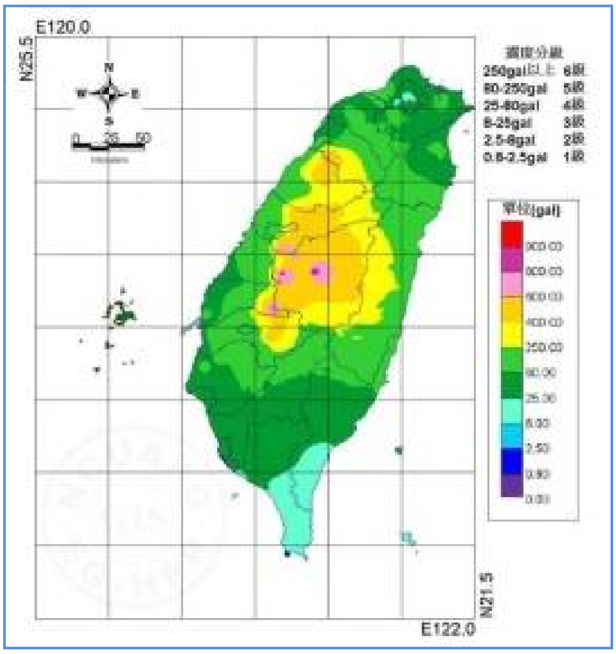


Figure 1: Magnitude of Chi-Chi Earthquake on September 21, 1999

TANFB reviewed the seismic vulnerability of all freeway bridges after the Chi-Chi Earthquake, with the technical support by T.Y. Lin International Taiwan Inc. and the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. Bridges inventories are screened to identify structures that are seismically deficient and evaluated for the severity of expected damage and losses by using TELES to prioritize in the order of needs for retrofitting. Based on the seismic vulnerability rating results, the Taiwan freeway bridge seismic retrofit program covers three phases of implementation: Phase I-freeway No. 1 (including widening project of freeway No. 2) and Phase II-freeway No. 3 (Northern Section) have been completed as of today. Phase III-freeway No.3 (Central and Southern Sections) and freeway Nos. 4, 5, 6, 8, and 10 are currently under the seismic evaluation and retrofit design stage.

TANFB reviewed and evaluated the existing freeway bridge according to the "Specifications for Seismic Design of Highway Bridges" issued by the Ministry of Transportation and Communications (MOTC) in Taiwan. For those bridges not conforming to the latest seismic design specifications, seismic retrofit becomes essential to minimize the damage from future earthquakes and to maintain functional serviceability of **Lifeline** for successful emergency disaster relief after large earthquakes. The retrofit measures used within the program include installing isolation bearings, dampers, shock transmission units (STUs), restraining devices to prevent unseating, steel jacketing, concrete jacketing, FRP jacketing, infill shear wall, link-beam and supplemental piles, etc.

2. FREEWAY BRIDGE SEISMIC RETROFIT PROGRAM

2.1 Project Objectives

Taiwan government completed the "TAIWAN AGENDA 21- Plans of Sustainable Development Strategy" in May 2000. The disaster prevention, industry and transportation development mentioned in the strategic plans depend on the overall improvement of seismic performance for Taiwan national freeway system. The win-win situation concerning both safety and economy is achieved by using the risk management concepts, shown in Figure 2. The seismic retrofit project aims at the following four general objectives:

- To reduce damage and to avoid casualties of future large earthquakes is the primary objective.
- To construct Taiwan's high-efficiency **Lifeline** for earthquake disaster relief roadway network system.
- To ensure high-safety critical transportation infrastructures for Taiwan's economic sustainable development.
- To achieve the overall goal of disaster prevention by adopting the seismic performance concepts- "Zero damage for frequent earthquakes; Reparable damages under moderate earthquakes; No collapse in the case of extreme earthquakes".

Figure 2: Risk management concepts for disaster prevention

2.2 Project Scope

Based on the seismic vulnerability rating results and prioritization studies by using TELES, Taiwan freeway bridge seismic retrofit program are being executed sequentially. TANFB propose tender procurement strategy involving the maintenance and construction jurisdiction of the three Region Engineering Offices and one Freeway

Construction Office. The project scope, number of bridges and schedule of individual phase are shown in Table 1 and Figure 3 (T.Y. Lin Taiwan, 2015).

Table 1: The scope of Taiwan freeway bridge seismic retrofit project

Project phases	Project scope	Number of bridges evaluated	Number of bridges retrofitted	Description
Phase I	Freeway No. 1 and No. 2 (including the widening projects of freeway No. 1 Yuanlin-Kaohsiung section and freeway No. 2)	490	412	Freeway No. 1: completion in December 2009 Freeway No. 2: completion in December 2011
Phase II	Freeway No. 3 (northern section)	190	180	Completion in June 2016
Phase III	Freeway No. 3 (central and southern sections) and freeway Nos. 4, 5, 6, 8, and 10	769	Note 1	In the seismic evaluation and retrofit design stage, scheduled for 2016~2025

Note 1: according to seismic assessment results to determine the number of bridge retrofitted.

Figure 3: Phased execution plan of Taiwan freeway bridge seismic retrofit project

2.3 Prioritization by Using TELES

The Taiwan Earthquake Loss Estimation System (TELES) developed by NCREE offers automation in complete seismic loss estimate within a short time frame after receiving earthquake warning notice through e-mail from the Central Weather Bureau (CWB), and then transmits instantaneous messages to emergency response personnel at the Central Emergency Operation Center for activating emergency responses in casualty and loss control. The TELES provides informative estimates (damages, injuries, casualties, rescue and medical-caring demands, etc.) following the disaster reduction plans. It has also been applied to the Taiwan Residential Earthquake Insurance Fund for improving residential earthquake insurance scheme in Taiwan. Finally, the prioritization of seismic retrofit scheme of freeway and highway bridges system is made possible by TELES.

The analysis modules contained in TELES are roughly divided into four groups, namely the potential earth science hazards (PESH), the direct physical damages, the indirect physical damages, and the socio-economic losses, as shown in Figure 4 (Yeh et al., 2006).

As shown in Figure 4, the integration of probabilistic seismic hazard analysis in the TELES framework helps to identify the maximum probable earthquakes at each county/city. The system evaluates seismic risk of various facilities and lifeline systems in different regions and facilitates decision making on adequate risk management in accordance with results obtained from the prioritized seismic retrofit and seismic performance of bridges.

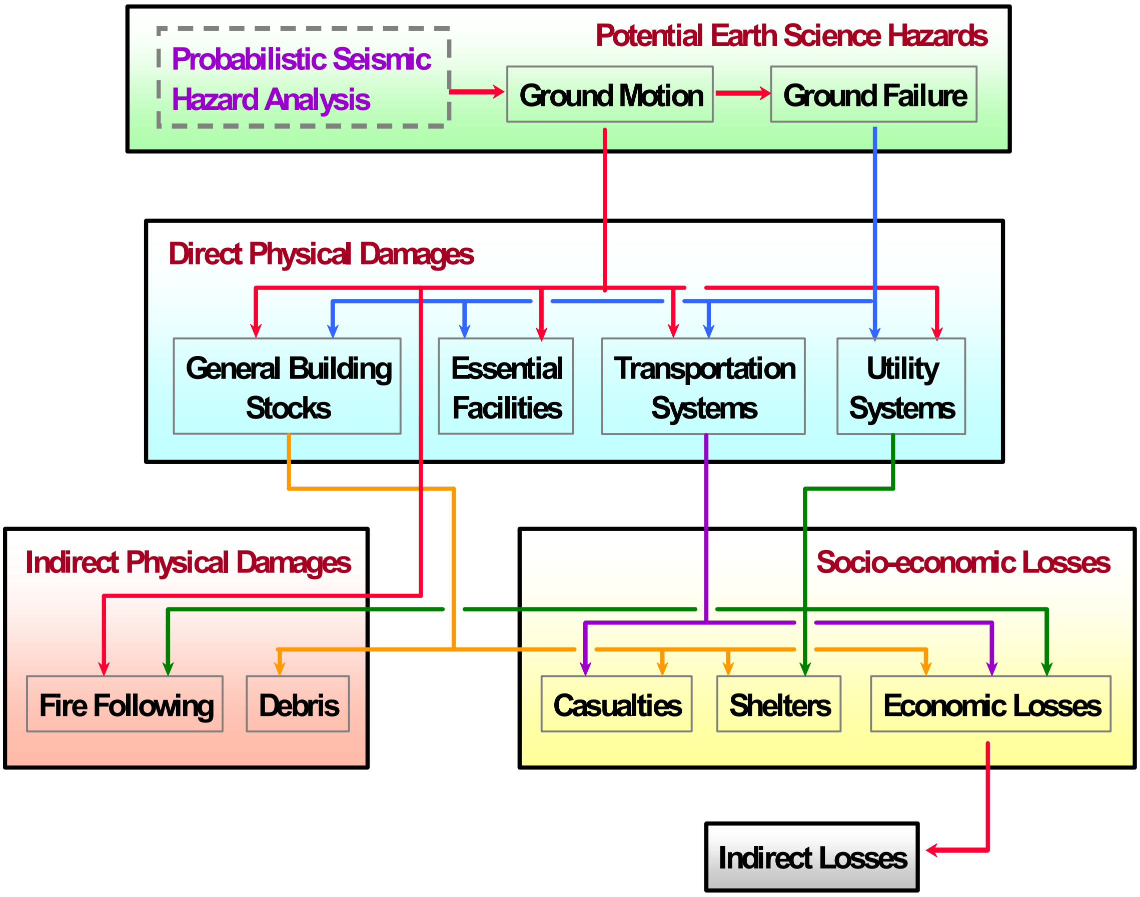


Figure 4: Framework of Taiwan Earthquake Loss Estimation System (TELES)

Figure 5 shows the earthquake damage assessment models and analytical processes of highway bridges in TELES. Depending on earthquake magnitude, the shortest distance to fault rupture surface (or line) and soil properties in various regions, i.e. earthquake attenuation law and site effects modification model, the site-specific ground motion intensity is calculated for each bridge. The ground motion intensity is derived from Peak Ground Acceleration (PGA) and structural Spectral Acceleration (S_a). The extent of structural damage during an earthquake event is quantified in terms of seismic response. Bridge fragility curves adopt 1.0-sec period spectral acceleration coefficient as the evaluation parameter for damage assessment in TELES.

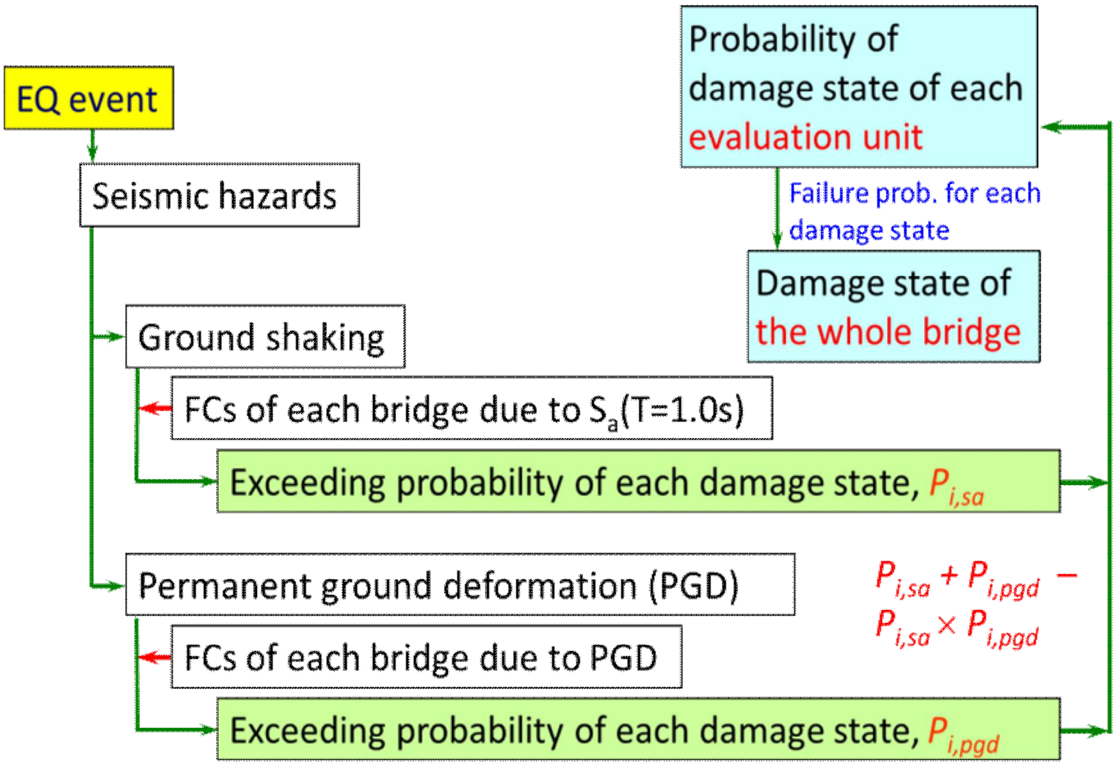


Figure 5: Earthquake damage assessment of highway bridges in TELES

The earthquake loss assessment of the freeway bridges is classified as direct loss and indirect loss. Direct loss is the expected repair cost for the damaged bridges caused by simulated earthquakes. Indirect loss is based on the increased traveling time and distance as a result of detouring in the regional road networks due to the freeway traffic blockade caused by bridge damage. According to the results of "Research of Intercity Transportation System Demand Model for National Sustainable Development, Phase-4" conducted by Institute of Transportation, Ministry of Transportation and Communications (MOTC), the traffic scenarios due to the bridge closure are simulated by using the GIS-based TransCAD transportation planning software. The traffic loss after the bridge damage is assessed, and finally the transformation is to be made from time value and driving energy depletion to equivalent currency, which is considered as the indirect traffic loss of the freeway system in the simulated earthquake event.

As Taiwan freeway is a toll-charged closed network, entering and exiting the freeway must go through the interchanges. If there is any one bridge closed due to earthquake between two interchanges, this section will immediately be out of function. As a result, the freeway projects, regardless of new construction, widening, and seismic retrofitted, are conducted section by section in compliance with engineering practice in Taiwan. When the seismic risk of freeway bridges are being assessed in phase III, the freeway are divided into 88 sections by interchanges, where one or two more bridges might be included in one section. Therefore, the direct loss and indirect loss in the simulated earthquake event are shown in sections by considering the results of the earthquake loss assessment of each bridge in the section.

Moreover, by applying the TELES probabilistic model of seismic risk assessment to presume various scenarios of seismic simulations, and combining the seismic event loss data sheets and the seismic source probability model, the average annual loss and the annual exceedance probability are calculated based on theory of probability and statistics. Then, the results of risk assessment for the 88 freeway sections can be calculated before/after seismic retrofit, for the sake of prioritization of seismic retrofit.

The results of risk assessment for 88 sections before/after seismic retrofit in phase III are summarized in Table 2. In general, after retrofit, the average annual loss decreases significantly to NT$ 129 million, merely 16.69% of that before retrofit. It shows that after retrofit, seismic risk loss can be reduced by 80%, clearly demonstrating the efficiency of retrofit in improving seismic risk of freeway bridges.

Table 2: Average annual loss of freeway bridges before/after retrofit in phase III

	Direct loss	Indirect loss	Total loss
Before retrofit	430,662	345,971	776,632
After retrofit	51,985	77,644	129,630

Unit: in thousand NT$

With the average annual loss of each bridge and section before/after retrofit from seismic risk assessment, comparisons between the average annual loss before and after seismic retrofit can be taken as a reference to prioritization study for retrofit.

In order to have a reasonable and objective criterion for retrofit prioritization for the freeway bridges in phase III, there are two main evaluation factors: Seismic Vulnerability (SV-factor) and Traffic Economic Impact (TEI-factor). Based on these two factors, various indices of retrofit prioritization have been designed to quantitatively describe the difference among various sections. In addition, in order to evaluate the degree of importance among the various indices, the indices are scaled from the least to the most important one in terms of value between 0 to 1. The detail definitions of the indices are described as follows.

2.3.1 Seismic Vulnerability

- Risk Index of Sectional Loss: Considering the seismic risk of the bridge structures in the section, the results of seismic risk assessment before retrofit (average annual direct loss) are taken as the loss risk of each section.
- Benefit Index of Sectional Retrofit: The amount of reduced risk for earthquake loss is considered as the benefit of bridge seismic retrofit. By dividing or deducting the construction cost of retrofit, comparison is made to assess the benefit value of sectional retrofit.

- Preliminary Scores of Sectional Seismic Vulnerability Assessment: After T.Y. Lin International Taiwan conducted the inspection of bridges, preliminary assessment has been done and scoring sheets have been filled with the consideration of bridge unseating and bridge strength/ductility. By averaging two scores based on the section where the bridge is located in, the preliminarily assessed average scores of unseating and strength/ductility for all bridges per section can be obtained.

2.3.2 Economic Impact

- Risk Index of Traffic Detouring: By using TransCAD system to consider the condition of section blockade, additional total traveling time and distance caused by traffic detouring are obtained. Then, the average annual indirect loss of each section calculated by TELES seismic loss risk model is regarded as the risk index of traffic detouring.
- Industrial Economic Impact Index: Where there is important traffic node in the section which serves the areas such as cities, airports, ports, science and technology parks, or industrial parks located within 30 km radius, the index scores are given in order to reflect the difference of economic impacts.

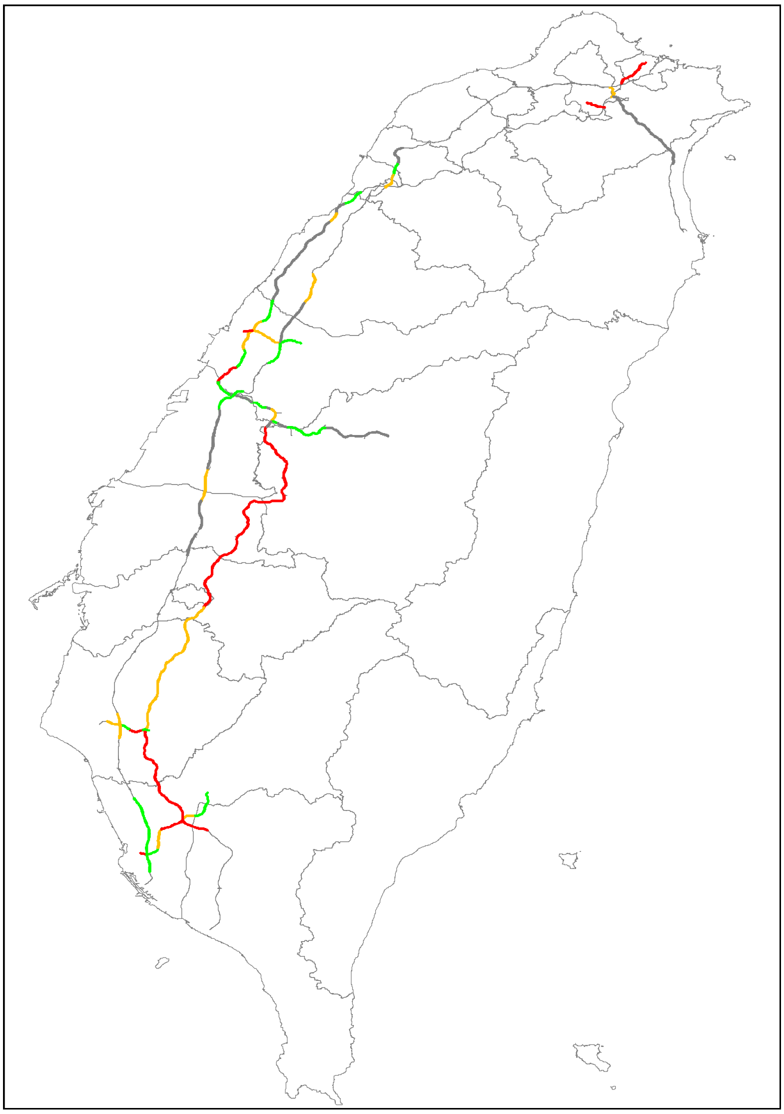


Figure 6: Prioritization scores of each section in phase III

- Risk Index of Crossing Critical Facilities: When severe bridge damage occurs, the impact on the critical facilities under the damaged overpass happens as well, such as Taiwan High Speed Rail, Taiwan railways, highways, or urban viaducts. The index reflects the impact on the crossed facilities.

The prioritizing indices are calculated with different weights. Then, weighted scores of each section can be obtained as a basis to assess priority of seismic retrofit, as shown in Figure 6.

Based on the above prioritization study results and the jurisdiction areas of Region Engineering Offices of TANFB, retrofit project phase III is further divided into 3 prioritized sections and is recommended to implement during 2016~2025.

2.4 Bridge Seismic Performance Criteria

The seismic retrofit standard of the existing bridges on national freeway should be 50-year anticipated service life, and the effect of river scouring and stability of slope should also be considered. In the seismic evaluation and retrofit design of bridges, if the retrofit construction cost exceeds 45% of a new bridge construction cost of the same type, the rationality of retrofit design deserves further review and evaluation.

As the national freeway is the most important lifeline and disaster relief roadway network in Taiwan, the seismic performance criteria for bridges identified for this project are shown in Table 3.

Table 3: Seismic performance criteria of bridge retrofit

Earthquake ground motion	Design earthquake response spectral acceleration coefficient		Seismic principles: Expected element behaviors	Post earthquake service level	Post earthquake damage level
Moderate Level Earthquake (MLE) DLE/3.25	Site Specific		Structures remain linear or nonlinear elastic	Immediate: Normal traffic after earthquake	**Minimal**
	1/3.25 of Design Level Earthquake (475 years return period)				
Design Level Earthquake (DLE) Return period: 475 years 10% probability of exceedance in 50 years	Site Specific		Members form plastic hinge and reach their allowable ductility capacity	Limited: Limited traffic after earthquake	**Repairable**
	S_S^D	0.80, 0.70, 0.60, 0.50			
	S_1^D	0.45, 0.40, 0.35, 0.30			
Maximum Credible Earthquake (MCE) Return period: 2,500 years 2% probability of exceedance in 50 years	Site Specific		Members form plastic hinge and reach their ultimate ductility capacity; No Collapse	Emergent: Emergent traffic after earthquake	**Significant**
	S_S^M	1.00, 0.90, 0.80, 0.70			
	S_1^M	0.55, 0.50, 0.45, 0.40			

2.4.1 Considerations of Active Faults

According to active faults map, shown in Figure 5, published by the Central Geological Survey, Ministry of Economic Affairs (MOEA) in May 2010, several national freeway bridges within the project are in the vicinity of active faults. The near-fault effect is of significant concern in the seismic evaluation process.

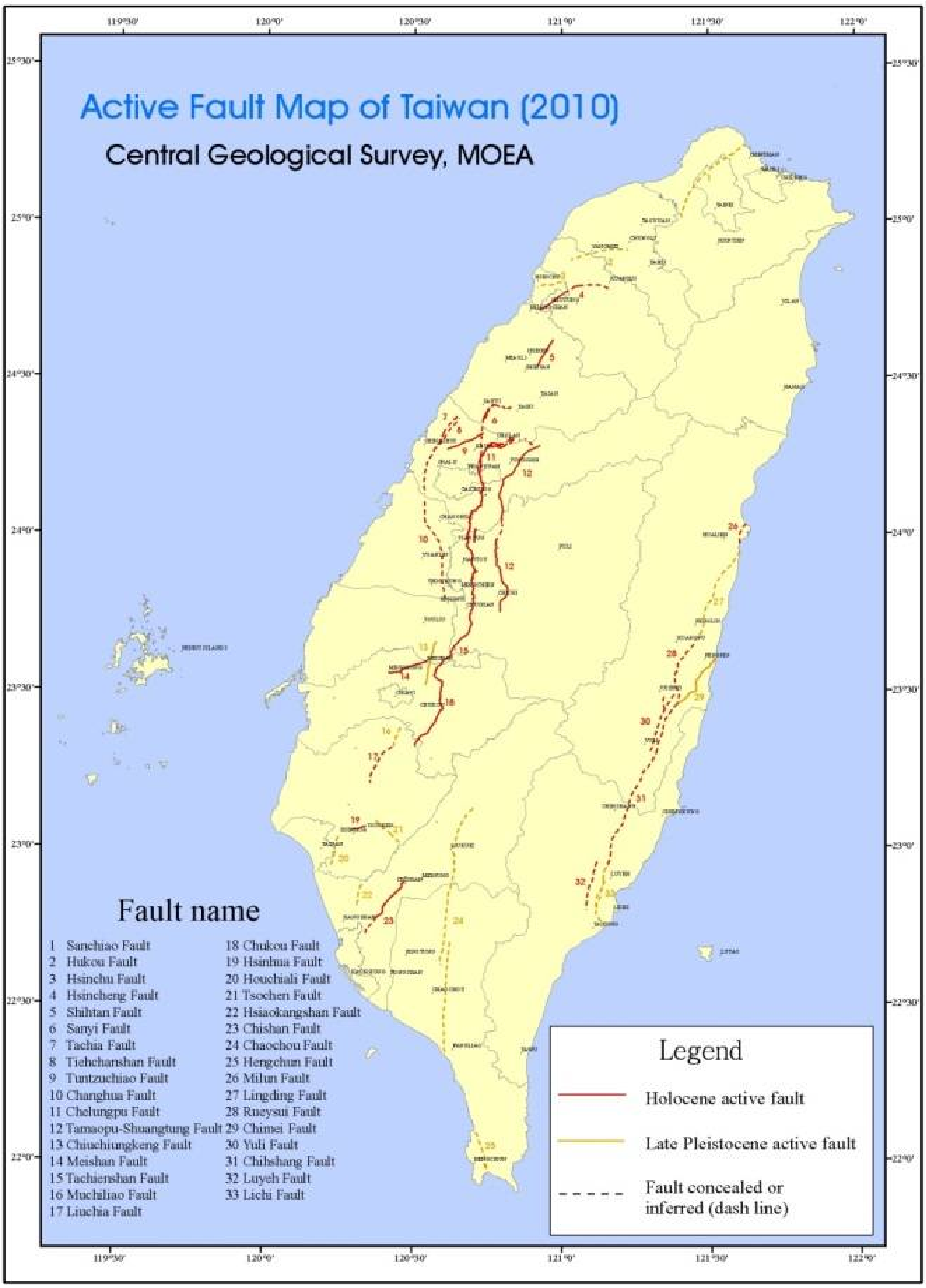


Figure 5: Active fault map of Taiwan (2010)

2.4.2 Considerations of Vertical Acceleration Effects near Faults

A few case studies on the behaviour of bridges under the impact of vertical accelerations suggest that these effects are not negligible. This is particularly true for some response parameters (such as superstructure moments and shears, and column axial forces) and certain bridge types (such as those with long flexible spans, C-shaped piers, or with other large eccentricities in the load path for vertical loads).

Based on the study of NCREE, the impact of vertical ground motion may be ignored only if the bridge is greater than 14 km away from an active fault. If the bridge site is within 14 km of an active fault, the site specific study is required once the response of the bridge is deemed significantly and adversely affected by vertical ground motions. In such cases, response spectra and acceleration time histories should be developed for use in the response analysis of the bridge. For the bridge near active faults, use of a vertical-to-horizontal spectral ratio of two-thirds throughout the period range is recommended unless the important vertical natural periods of vibration of the bridge are less than 0.2 second (FHWA, 2006).

In lieu of a dynamic analysis that explicitly includes the effect of vertical ground motion, the following variations in column axial loads and superstructure moments and shears are included in the seismic evaluation of the columns and superstructure to account for the effects of vertical ground motions.

- Column axial loads = $(1 \pm C_V)$ axial forces due to dead load.
- Superstructure bending moments = $(1 \pm C_V)$ bending moments due to dead load.
- Superstructure shears = $(1 \pm C_V)$ shears due to dead load.

Specific recommendations for C_V value are not provided in the Project Design Criteria until more information is revealed about the characteristics of vertical ground motion in Taiwan. However, it is advisable for designers to be aware that vertical acceleration effects may be important and should be assessed for bridges near fault by reference to Caltrans Seismic Design Criteria (2013) and FHWA Seismic Retrofitting Manual for Highway Structures: Part 1-Bridges (2006).

2.5 Bridge Seismic Evaluation Methods

The seismic evaluation of a bridge is explicitly or implicitly a two-step process. A demand analysis is required first to determine the forces and displacements imposed on the bridge by an earthquake; this is then followed by an assessment of the required capacity to withstand this seismic demand. The outcome of evaluation methods is capacity/demand ratios calculated on a component by-component basis, or for the bridge as a whole (i.e., as a single structural system) (Aviram et al., 2008).

2.5.1 Regular and Irregular Bridges: Structure Capacity/Demand Method

Seismic demands are derived from elastic methods such as the multi-mode response spectrum method, or an elastic time history method. The capacity assessment is based on the displacement capacity of individual piers or whole bridge as assessed by a “pushover” analysis, which includes the nonlinear behaviour of the inelastic components. This method is suitable for all regular bridges. It is also known as the Pushover Method or the Nonlinear Static Procedure alternatively.

A well-defined plastic hinge is the key point to ensure an accurate pushover analysis result. The commercial software SAP2000 is used to perform the pushover analysis. Pushover analysis features in SAP2000 include the implementation of FEMA 356 and fiber hinge option based on a pre-defined stress-strain relationship. Although SAP2000 provided some convenient default definition for the plastic hinge of RC member, it was found that the analytical results sometimes are not quite agreeable to the nonlinear time history analysis. Five points A~E are needed to be input to define the plastic hinge as shown in Figure 6. Where section AB represents the linear behaviour and sections B to E are the nonlinear parts of the plastic hinge model.

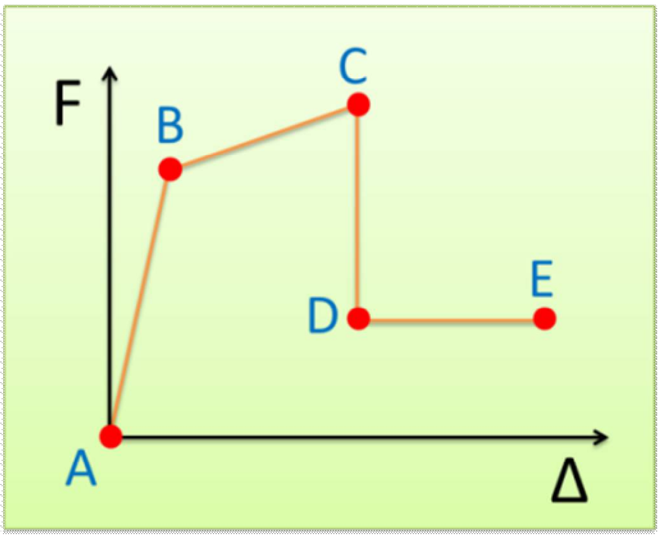
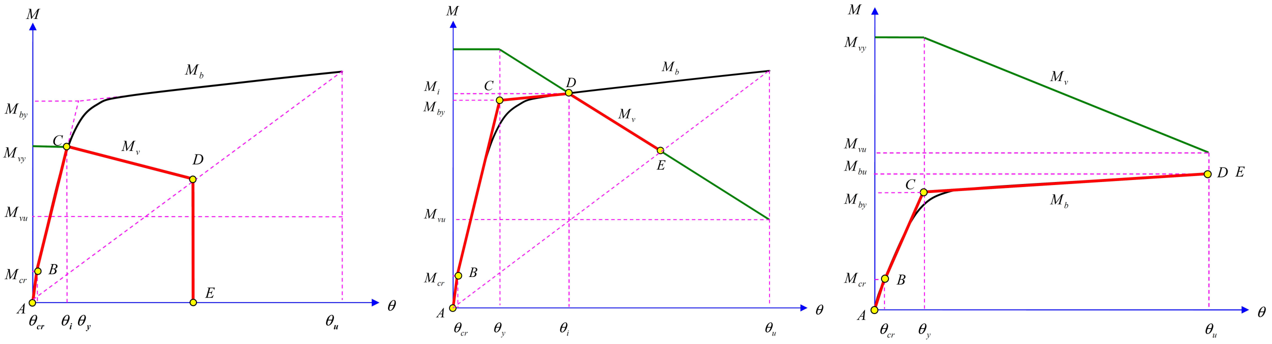


Figure 6: SAP2000 M3 plastic hinge model

In order to capture the actual behaviour of RC columns, and to get close simulation for the nonlinear behaviour, a modification of the default M3-hinge model in SAP2000 are developed. The three different failure modes, namely Shear failure, Flexure-Shear failure and Flexure failure are redefined, shown in Figure 7. The modified plastic hinge characteristic is used to replace the default M3-hinge model in SAP2000. With this modification, it improves the efficiency as well as accuracy of the pushover analysis for bridge seismic evaluation.



(a) Shear failure (b) Flexure-Shear failure (c) Flexure failure

Figure 7: Characteristics of plastic hinge for RC member

Researchers in Taiwan recommended to adopt the modified ATC-40 capacity spectrum method, in lieu of the seismic demands determined by elastic analysis and displacement magnification for short-period structures (Sung, 2003). In the curve of capacity spectrum, every performance points along the capacity curve are determined followed by a complete pushover analysis. Therefore, the curve is used as "input" to calculate the corresponding seismic demand as "output" and to bypass the complication resulting from ATC-40 method. The performance point is located at the interaction of capacity spectrum and demand spectrum, as shown in Figure 8. Such that spectral acceleration a_{pi} and displacement d_{pi} for the capacity spectrum would be the same as $(S_a)_{\text{inelastic}}$ and $(S_d)_{\text{inelastic}}$ for the inelastic demand spectrum.

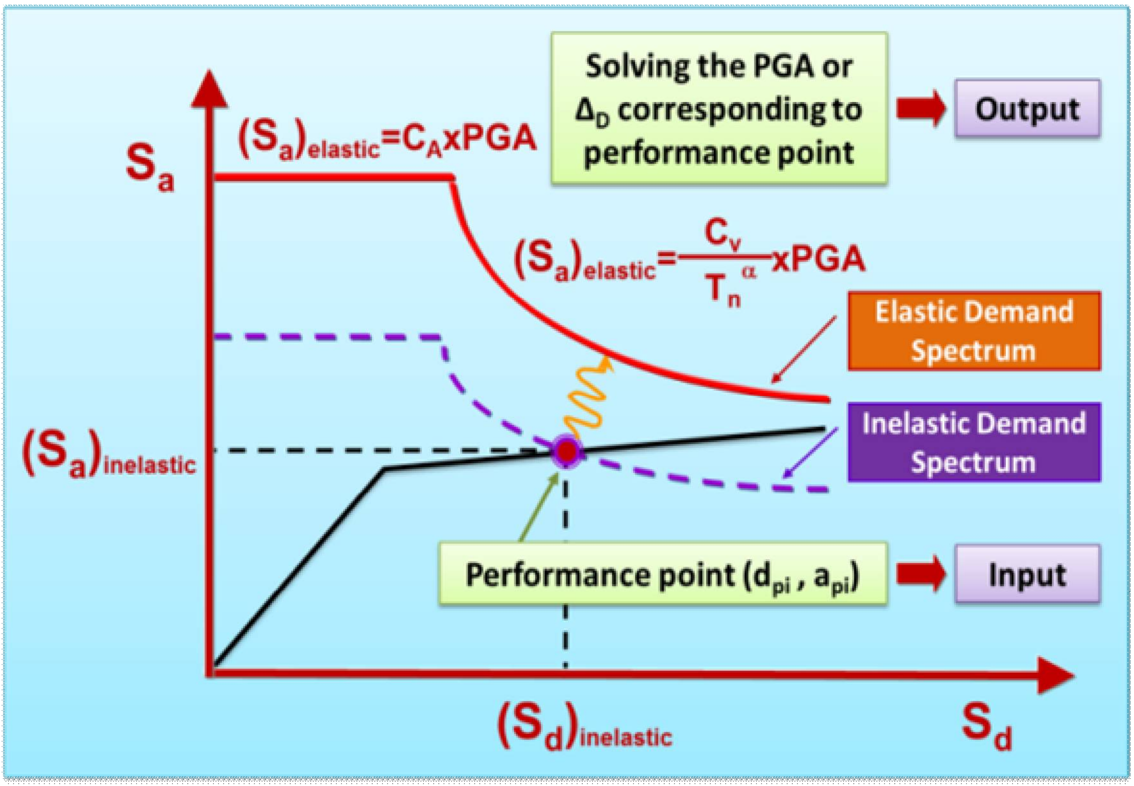


Figure 8: Capacity and demand spectrum

2.5.2 Irregular Complex Bridges: Nonlinear Dynamic Procedure

Seismic demands are determined by a nonlinear dynamic analysis using earthquake ground motion records to evaluate the displacement and force demands. Capacities of individual components are explicitly modelled in the demand analysis. This method is suitable for irregular complex bridges, or when site specific ground motions are to be used for a bridge of major importance.

2.6 Bridge Seismic Retrofit Measures

Care should be given to assess the structural response of the entire system for the three levels of earthquake demand in order to develop an effective seismic retrofit strategy. Prescribed processes may not apply to every situation. For example, yielding of a single element may not be sufficient to create a collapse mechanism. The redistribution of additional loads in a structural system after incremental yielding will be different for each structure; therefore, each structure should be thoroughly evaluated.

The objective of retrofitting a bridge is to ensure that it will perform satisfactorily when subjected to the three levels of earthquake. Specifically, bridges should be retrofitted to meet the performance criteria. Selecting the preferred retrofit strategy can be complicated. Not only is it often a challenge to find the right technical solution, it is also a challenge to satisfy a multitude demands from socio-economic constraints. Political and environmental constraints often arise during retrofitting in Taiwan and should be identified as far ahead as possible during selection of the preferred strategy.

There are some common approaches in Taiwan freeway bridge seismic retrofit project are listed below:

- Strengthening.
- Improvement of Displacement Capacity.
- Force Limitation (fuse and capacity-design concept).
- Response Modification.
- Site Remediation by Ground Improvement.
- Acceptance or Control of Damage to Specific Components.
- Partial Replacement.

Seismic retrofit measures have now been developed for deficient superstructures, bearings, beam seats, piers and columns, including weak cap beams and column-to-cap beam joints for more than a decade. In addition, techniques for improving the behavior of abutments and foundations have been developed, including measures for bridges on hazardous sites. This progress is the result of an aggressive research program conducted by NCREE (Chang et al., 2009) and overseas field experience, collected mainly in California and Japan.

A partial list of these measures adopted in Taiwan is as follows. Figures 9~24 illustrates some of the measures.

- Diaphragm strengthening.
- Provision of longitudinal continuity in simply supported spans.
- Replacement of bearings.
- Seismic isolation bearings.
- Energy dissipators (Fluid Viscous Dampers).
- Shock Transmission Units.
- Seat width extensions and catcher blocks at girder supports.
- Restrainers at girder supports and intermediate hinges.
- Column replacement.
- Concrete shells, steel and fiber-composite jackets for columns.
- Infill shear walls or link beam in bents.
- Cap beam strengthening using pre-stressing.
- Soil and gravity anchors.
- Abutment and column shear keys.
- Footing replacement or footing overlays.
- Supplemental piles (CIDH, CISS, and Micropile).

- Site remediation for unstable slopes and liquefaction.

Figure 9: Bearing seat extension and shear key

Figure 10: RC jacketing and aseismic block

Figure 11: RC and steel aseismic device

Figure 12: Transverse steel aseismic device

Figure 13: Longitudinal joint restrainers

Figure 14: STUs and maintenance catwalk

Figure 15: FVDs and shear keys

Figure 16: Steel jacketing and welding inspection

Figure 17: Steel jacketing and corrugated metal excavation

Figure 18: Column confined by a composite fiber/epoxy jacketing

Figure 19: Strengthening of pier cap and shear keys

Figure 20: Link beam for pier/pile cap for force reduction

Figure 21: Pier steel jacketing and scour protection

Figure 22: Steel jacketing on scoured piles

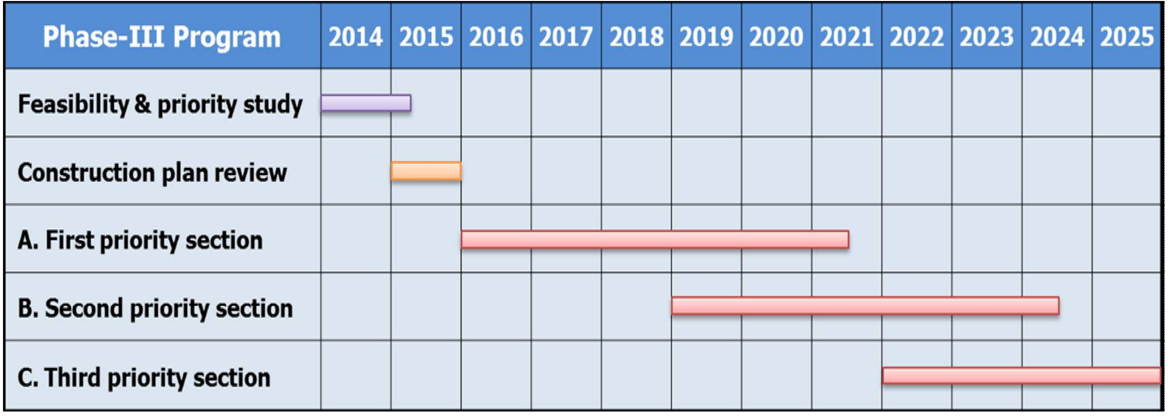
Figure 23: High capacity micropile

Figure 24: Micropile construction

2.7 Project Budget and Schedule

The Taiwan freeway bridge seismic retrofit program was planned and executed in three phases. As of today, Phase-I retrofit program covering the freeway No. 1 had been completed in December 2009 and freeway No. 2 in December 2011. The total cost of phase-I retrofit program are about NT$ 12.7 billion dollars. Phase-II retrofit program has completed in June 2016. The total cost of phase-II retrofit program reach up to NT$ 6.2 billion dollars at completion.

Table 4: Proposal schedule for phase-III seismic retrofit program



Phase-III Program	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
Feasibility & priority study	▬	▬										
Construction plan review		▬										
A. First priority section			▬	▬	▬	▬	▬	▬				
B. Second priority section						▬	▬	▬	▬	▬	▬	
C. Third priority section									▬	▬	▬	▬

Based on the prioritization study of TELES, the phase-III retrofit program is further divided into three priority sections and will be executed in 2016~2025, as shown in Table 4. The total funding of phase-III retrofit program are estimated around NT$ 33.8 billion dollars.

3. FUTURE OPPORTUNITIES AND ROLE OF TELES

3.1 T-BMS: National Bridge Database in Taiwan

In Taiwan, freeway and highway bridges are managed by various authorities. For example, local bridges are by city or county governments, provincial highway and expressway bridges by Directorate General of Highways (DGH), and freeway bridges by Taiwan Area National Freeway Bureau (TANFB). In order to unify the management and maintenance of all freeway and highway bridges, a platform called Taiwan Bridge Management System (T-BMS) was established in 2000. A national wide database of all bridges has also been collected and kept undated accordingly.

Such complete, integrated and shared database of bridges has brought significant benefits to the documentation of inspection, budget prioritization and allocation, and establishment of hazard mitigation program.

In 2009, a major revision of T-BMS was completed in order to enhance the system performance and user interface for better service. T-BMS is supported with real-time information of rainfall by the Central Weather Bureau, MOTC, as well as river water level by the Water Resources Agency, MOEA. Emergency personnel could be alerted to shutdown some of the bridges immediately for safety reason whenever a threshold of alert is exceeded. Therefore, T-BMS is featured with decision supporting capability to secure the safety of freeway and highway drivers under the circumstance of a typhoon, torrential rain or flood. Currently, T-BMS is under upgrade. The primary concerns of the new system, T-BMS 2.0, include: (1) calibration of bridge database; (2) supplementary structural and environmental data for multi-hazard mitigation; and (3) condition of and countermeasure for deterioration. There are several new features included, for example (1) generalization of 3D bridge model for data visualization; and (2) cloud service through cross-platform mobile APPs (Yau et al., 2015).

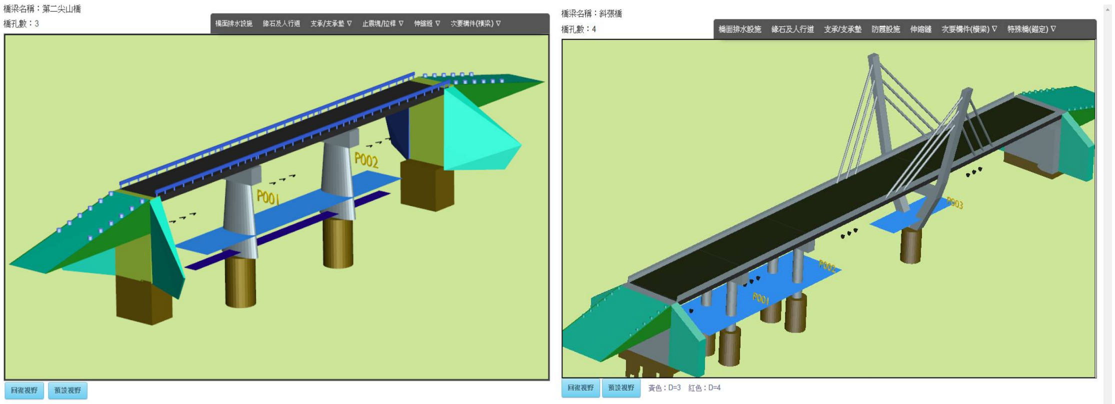

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Figure 25: Automatic generation of 3D bridge model in T-BMS 2.0 (after Yau et al., 2015)

A ready-for-use national wide bridge database has shed light into various implementations, and TELES for earthquake hazard mitigation and emergency response of freeway and highway bridges and networks is one among many.

3.2 TELES Early Seismic Loss Estimation for Emergency Response

In order to respond to an emergency state quickly and effectively, it is very important to have an early and comprehensive understanding of the disasters through assessment and field reconnaissance. However, the status of damage of a freeway and highway system following earthquakes is very difficult to assess. The system is usually widely spread in space, and some places of the system could be remote, making it difficult to assess the damages within a short time. The outage of power and telecommunication may delay the report of damage from the field. All these may delay the response of emergency officers as there is very limited information to make correct decisions regarding dispatch of personnel, equipment and materials. Therefore, it will be very valuable to decision-making during the early stage of earthquake emergency response if a technology capable of providing the predictions of the damage and serviceability of a freeway and highway system immediately after the occurrence of earthquake can be developed.

In the past decade, the technology of early seismic loss estimation (ESLE) has been developed and implemented (Yeh et al., 2006) in many fields in Taiwan by NCREE. The methodology of ESLE is as depicted in Figure 26. A seismic scenario database is built first. It contains simulated ground motions at the CWB real-time stations as well as the damage resulted from thousands of earthquakes, which well represent the collection of all possible earthquakes to occur. After the occurrence of a strong earthquake, the ESLE module can be automatically triggered by the earthquake alert email from the CWB. Several scenarios will be selected according to the following criteria: they have similar source parameters as the ones prescribed in the mail; the simulated PGA and the observed PGA at real-time strong motion stations are close to each other. As the selected scenarios are very close to the real event, it can be reasonably speculated that the corresponding damages and losses by simulation may be very close to the damages and losses in the real event. In a sense, the ESLE technology adopts every piece of information contained in the earthquake alert email from CWB.

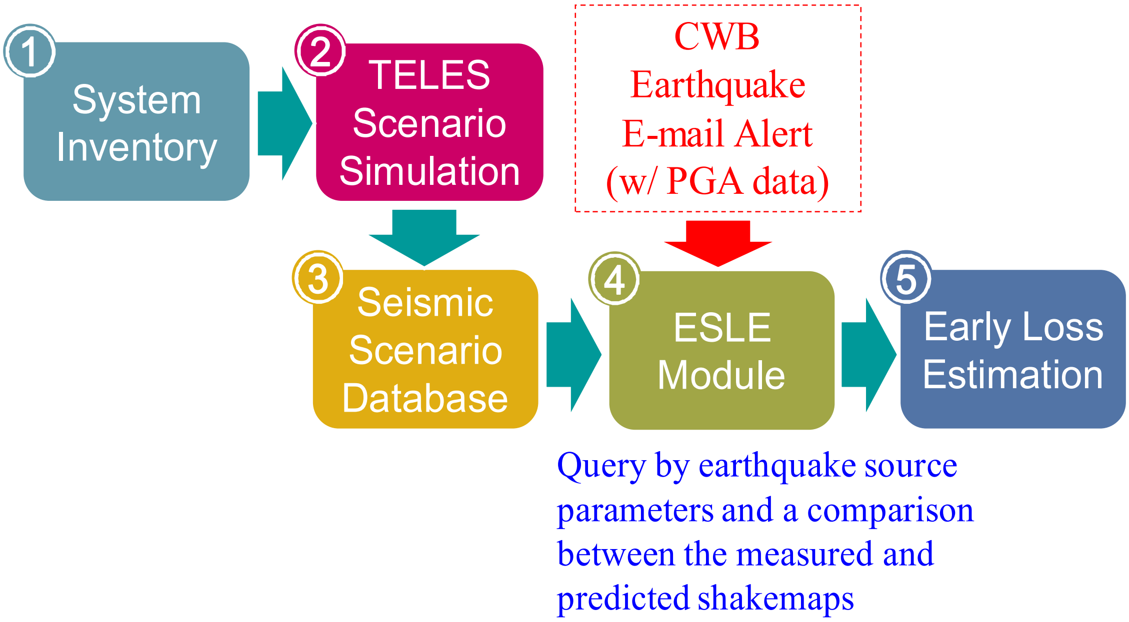

Figure 26: The flowchart of TELES early seismic loss estimation

3.3 TELES for a Safer New Era of Smart/Connected Highway Transportation

Thanks to the development and implementations of emerging information and communication technologies (ICT) in infrastructures, the way of using and managing highway transportation has changed significantly, and a quantum leap is about to come. This is a result of several game changers. The first is about Big Data capture, management and analysis in highway transportation. In Taiwan, T-BMS has been achieved as a huge and dynamic database of bridges national wise. Many of the most critical bridges have been instrumented for real time monitoring. ITV cameras have been installed for the inspection of traffic flow everywhere. Electronic Toll Collection (ETC) and Vehicle plate recognition have been implemented in all freeway systems, which can provide measures of traffic flow breakdown everywhere, too. Potentially, Big Data may enable a wide range of new strategies that are expected to provide safety, mobility and environmental benefits (Burt et al., 2014). In Taiwan, **SafeTaiwan** developed by Directorate General of Highways (DGH) plays the role of a risk management collaboration platform. It has secured the safety of highway drivers by managing meteorological data and timely closing some of the routes exposed threat in past hazardous events.

Figure 27: SafeTaiwan- Risk Management Collaboration Platform (after DGH, 2014)

The second is about the internet of things (IoT) in highway transportation to make it a smart system. Known as Vehicle to Vehicle (V2V) and Vehicle to Infrastructure (V2I) and others, smart/connected transportation is supported by ICT that transmit and process data about all sorts of activities within. Vehicles, travellers, and infrastructure in the system can communicate with each other through various data streams (Cuddy et al., 2014). Smart highway transportation system can cooperate with the other systems which are constantly collecting data (e.g. a system for hazard early warning) to help handle emergencies or disasters. In Japan, a vehicle-infrastructure cooperative system installed in 2011 has made possible various services in an "all-in-one" system. Services are provided to on-board units in vehicles via "ITS Spots" (Nishio, 2012).

The third is about self-driving cars (autonomous vehicles, AUVs). The research by Gerla et al. (2014) concludes that: The evolution from manually operated to autonomous vehicles will pose several new challenges and opportunities. For example, after a disaster, it is crucial to maintain a V2V supported propagation of traffic conditions and congestion state of the road network to avoid a second disaster. This background "crowd sourcing" of traffic will allow the AUVs to make intelligent routing decisions to avoid obstacles or blocked roads in case of earthquakes.

In many ways, TELES should deeply engage with the analysis and utilization of Big Data of highway transportation. Multiple and interdisciplinary seismic scenario simulation should be conducted before an earthquake. This will help achieve improved planning by taking into account the full spectra of highway serviceability and adopt the best measures of hazard mitigation. The end users of the freeway and highway transportation from large and interconnected urban and suburban areas can be optimally served if sufficient redundancy in the network of transportation has been placed in advance, and traffic flows are capable of being wisely redirected if needed. TELES should also be engage in cross-agency collaboration to develop customized post-earthquake information services. TELES is featured with the capability of early seismic loss estimation (ESLE) to provide timely and reliable estimates of the damage in freeway and highway transportation. An intelligent transportation system (ITS) will be able to respond to the disastrous situation immediately and automatically according to the alert provided by the ESLE report. V2V and V2I infrastructures in the system will be able to handle the associated information streams needed to drivers and vehicles on the affected routes, and to the emergency personnel assigned to road closure and bridge inspection.

4. CONCLUSION

After Chi-Chi earthquake struck Taiwan on September 21 1999, TANFB has completed the seismic retrofit of the most important lifeline in Taiwan (freeway No.1) within 10 years. TANFB, T.Y. Lin International Taiwan and NCREE formed a joined effort to complete freeway bridges seismic hazard mitigation project by using TELES.

Some common retrofit measures in Taiwan have been identified during the project execution while several innovative devices and construction technology are developed including the use of fluid viscous damper, shock transmission units, column jacketing, and other measures of column confinement, restraining devices to prevent unseating, and the use of shear keys and keeper brackets to limit transverse deck movement.

This paper updates the latest development of Taiwan freeway bridge seismic retrofit project. The lessons learned and knowledge gained are tremendous. As for individual bridge engineer or many regions being threatened by earthquakes, the state-of-the-art technology used in the project may also be adopted in other seismic region. The information concluded in the paper also promotes the awareness of overall bridge seismic retrofit program in a region where resources and funding allocation may be optimized from a systematic perspective.

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