Seismic Retrofitting Principles and Measures on US Highway Bridges

W. Phillip Yen, Ph.D., P.E.

INSTRUCTION

Background

Our highways are built to transport goods and people, and connect nations, states and cities. As such, they are our lifelines to deliver daily needs such as food, water, and communication with other locations. Built to serve human needs in this modern world, they are also constructed to resist all natural hazards and protect our lives and properties. As a result of natural hazards in the U.S. from 1993-1996, approximately one quarter billion dollars per week was spent on meteorological natural disasters [FEMA, 1997]. Among these natural hazards, earthquakes, hurricanes and floods were the major causes of monetary loss. Figure 1.1 compares the impacts of most costly natural disasters in the U.S. from 1988 –1997.

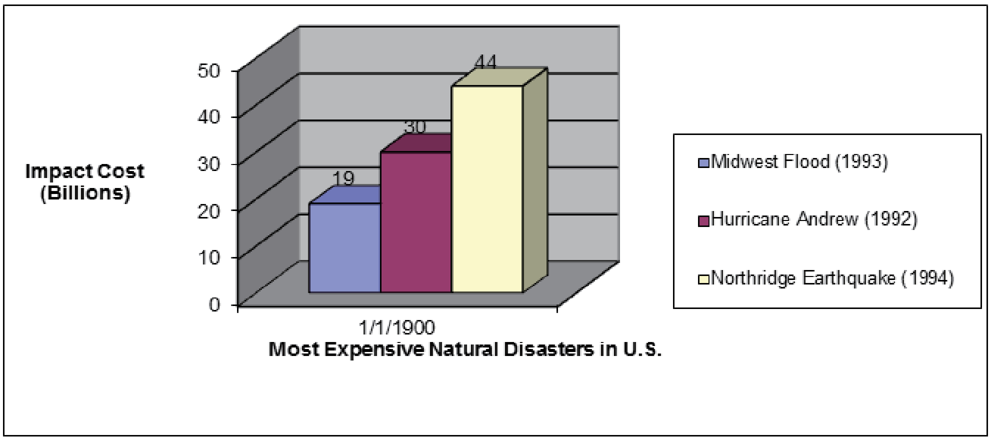

Figure 1.1 Impact of Natural Hazards

Earthquake Hazard

An earthquake is a sudden ground motion or trembling caused by an abrupt release of accumulated strains acting on the tectonic plates that comprise the Earth's crust. They often trigger other devastating events such as lateral spreads, landslides and fires; and damage bridges, buildings, dams and other infrastructure components. An earthquake may also add a Tsunami to coastal areas if it triggers in the ocean. Although the probability of large destructive earthquakes is relatively much lower than other natural hazards such as hurricanes and floods, an earthquake can, without warning, devastate an area within one to two minutes through ground shaking, surface fault rupture and ground failures.

美國耐震補強原則與標準

顏文暉
國際橋梁地震委員會主席

背景介紹

高速公路建造的目的是在城市、州與州之間，甚至與其他國家相通，以運送貨物和人群。正因為如此，高速公路常常也用於每天運送人民維生所需的糧食、飲水，並且維繫和其他國家之間的通訊。在科技進步的今天，高速公路為滿足人類基本的需求，必須在建造的時候能夠考量抵抗各種天然的災害，並且保障人民的生命安全及財產。從西元 1993 年到 1996 年之間，所有在美國發生的天然災害的統計來看，平均每一星期政府需要耗費七億五千萬美金，用於修復因氣候所造成的天然災害的工作上〔FEMA1997〕。而在眾多的天然災害之中，又以地震、颶風及洪水三項，造成最大筆金額的災損。圖 1 顯示在西元 1988 年至 1997 年，曾發生在美國耗費最高成本天然災害的比較圖。

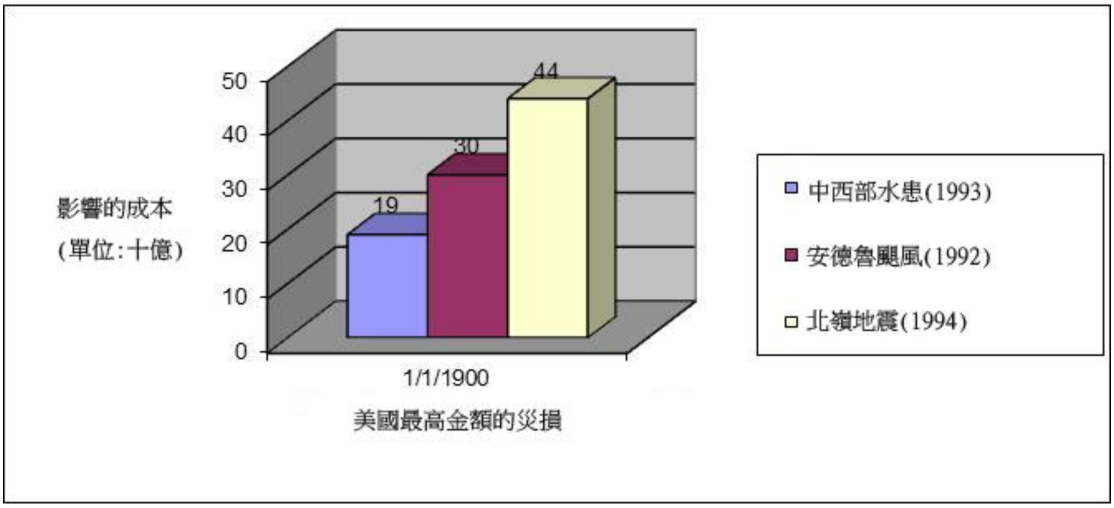

圖 1.天然災害的影響

地震災害

地震肇因於地球板塊之間，將累積的應變量以突發性的釋放所造成的地層活動，地震往往引發許多種的災害，如橫向力的位移、土石崩塌、火災，並對於橋梁、建築物、水壩及其他基礎建設的損害。地震若震央在海洋內，常常在靠海岸地區產生海嘯。雖然比起颶風和水患等天然災害發生的頻率而言，地震的機率並不高，但是卻因地震常常是在無法預測的情況發生，並透過短短一、兩分鐘的地表搖晃、地表斷層的錯動和崩塌造成重大災損。

The loss of life and extensive property damage inflicted by the 1989 Loma Prieta, and 1994 Northridge earthquakes emphasized the need to minimize earthquake risks to our highway system. Table 1.1 summarizes the damage from significant American earthquakes (Stover and Coffman) between 1964 - 1994.

Table 1.1 Significant Earthquake Damages in the U.S. 1964-1994

Location	Date	Magnitude	Damages (in Millions)	Deaths
Prince William Sound, AK	03/27/1964	8.4	$311.0	125
San Fernando, CA	02/09/1971	6.6	$505.0	65
Loma Prieta, CA	10/17/1989	7.1	$6,000.0	63
Northridge, CA	01/17/1994	6.7	$20,000.0	61

(Sources: From Stover and Coffman, 1993, FEMA 1994)

Mitigation approaches discussed in this paper include new planning (seismic risk assessment method), structural design and retrofitting measures from the Federal Highway Administration's (FHWA) various seismic research projects.

SEISMIC VULNERABILITY AND HAZARD

Seismic Hazard Maps (USGS) & Ground Motion

Bridge design to resist earthquake is required to understand the seismic vulnerability or earthquake intensity of the bridge location. This vulnerability is usually described in terms of seismic hazard. The U.S. Geological Survey (USGS) National Seismic Hazard Maps display earthquake ground motions for various probability levels across the United States and are applied in seismic provisions of building codes, insurance rate structures, risk assessments, and other public policy. This update of the maps incorporates new findings on earthquake ground shaking, faults, seismicity, and geodesy. The resulting maps are derived from seismic hazard curves calculated on a grid of sites across the United States that describe the frequency of exceeding a set of ground motions. Currently, the seismic new design and seismic retrofitting criteria uses 1000-year return period which is about 7% of probability not to exceed the design life of 75 years. AASHTO works with USGS and published a set of Seismic Hazard Maps for the whole US and issued a CD with a computer program tool to obtain the seismic hazard or ground motion by enter either zip code or longitudes & latitudes.

Geotechnical Hazard

Another factor to add on the highway bridges and constructions is geotechnical hazard. Geotechnical hazards at highway bridge sites that can be triggered by earthquakes include soil liquefaction, soil settlement, slope failure (landslides and rock falls), surface fault rupture, and flooding. Assessing geotechnical hazards is a two-part procedure. In the first part, a quick screening evaluation is conducted. Generally, this can be accomplished using available information and field reconnaissance.

經過西元 1989 年發生在洛馬培塔及 1994 年的北嶺地震所產生的傷亡和慘痛的財務損失之後，使得政府開始重視降低地震對高速公路系統所造成的風險。表 1 將介於 1964 年到 1994 年之間在美國所發生過最嚴重的地震排列出來。

表 1. 美國 1964-1994 之間地震災損統計表

地點	時間	規模	災損(百萬美元)	死亡人口
阿拉斯加-威廉	03/27/1964	8.4	$311.0	125
加州-聖佛南多地震	02/09/1971	6.6	$505.0	65
加州-洛馬培塔地震	10/17/1989	7.1	$6,000.0	63
加州-北嶺地震	01/17/1994	6.7	$20,000.0	61

（資料來源：Stover and Coffman 1993, FEMA 1994）

在本文中所討論到災害防救的原則，包含各種聯邦高速公路管理局過去委外或執行的各項研發計畫，所涵蓋完整的事前規劃（地震風險評估方法），結構設計及耐震補強等成果。

地震易損度及災害

在進行橋梁設計的時候，首先需要瞭解地震對橋梁的易損度，或是對於橋址所在地的地震強度有充分認知。橋梁的易損度通常是以地震災害的程度來表示，美國國家地理調查局（USGS）負責製作美國國家地震災害地圖，將全國各種不同程度的地表運動描述出來，並且此圖也出現在建築設計規劃、震災保險費率計算的結構，用於風險評估及其他各類的公共政策中。每一版這類地圖的更新時，都會納入最新地殼的運動、新斷層的發現、地震學以及新的地質狀況的調查結果。最終這項災損的地圖也都經過在全美國地理分割後的網格內，製作的災害曲線所計算出來的，並且以超過某種規模地震的機率作為基礎。如今，最新的地震設計規範和耐震補強的標準都是以 1,000 年回歸期為基準，並且以 75 年生命週期不超過 7%的機率製作。而美國國家州政府交通官員協會（AASHTO）結合美國國家地理調查局（USGS）的研究成果，出版了一套全國的地震災害地圖的光碟，並且提供一套軟體，只要輸入查詢工址所在的郵遞區號或是東經、北緯的座標值，就可以獲得該工址內地震災害或是地表運動規模的地圖。

地質災害

在地震災損的評估時，橋梁的易損度也參考了地質條件的因素，而因為地質條件的不同，所產生的橋址處的影響因子包含：土壤的液化、沈陷、邊坡破壞（地表滑動及岩石錯動），斷層破壞及淹水區等。針對地質破壞的評估可概分為兩個步驟，首先需要經過一個快速的篩檢評估。一般而言，僅需透過可利用的工址資訊及現場調查即可完成。

If the criteria are satisfied, the risk is considered to be low and further evaluations of the hazard are not required. If a hazard cannot be screened out, more detailed evaluations are conducted in the second part of this procedure. This usually requires obtaining additional data to more rigorously assess the hazard and its consequences.

Assessment of Infrastructure Vulnerability

To assess the bridge inventory in the seismic vulnerability, a method, called Indices Method is often used. In this method, the seismic rating of a bridge is determined by its structural vulnerability, the seismic and geotechnical hazards at the site, and the socioeconomic factors affecting the importance of the structure. Ratings of each bridge are first found in terms of vulnerability and hazard, and then modified by importance (societal and economic issues) and other issues (redundancy and non-seismic structural issues) as necessary to obtain a final, ordered determination of retrofitting priority (Buckle, 1991; FHWA, 1995). This rating system has two parts: quantitative and qualitative. The quantitative part produces a seismic rating (‘bridge rank’) based on structural vulnerability and site hazard. The qualitative part modifies the rank in a subjective way that accounts for importance, network redundancy, non-seismic deficiencies, remaining useful life, and similar issues to arrive at an overall priority index.

HAZARD MITIGATION MEASURES

Seismic Design

The performance of US highway bridges in recent large earthquakes has shown that good design details have saved many bridges from collapse due to unseating of superstructure or shear failure of columns. Seismic design methods have evolved over the past 30 years and have produced details that directly affect bridge performance under earthquake and other natural hazard loadings. Design methods have steadily improved based on experience with destructive earthquakes and advanced seismic research.

The current seismic design specification, adopted as a standard in 1992 by AASHTO, was primarily developed by US highway agencies, including FHWA and CALTRANS. Realistic seismic provisions first entered this code after the 1971 San Fernando earthquake. The fundamental design objective of the current seismic specifications is to prevent collapse in large earthquakes. In small to moderate events, the intent of the code is to resist seismic loads within the elastic range without significant damage to structural components. The objective in large earthquakes is that no span, or part of a span, should collapse. However, the AASHTO specifications consider limited damage to be acceptable in these circumstances, provided it is limited to flexural hinging in pier columns. Further, it is desirable that the damage occurs above ground in regions that are visible and accessible for inspection and repair.

Design Performance Criteria

如果某些條件充份滿足，且地震的風險被認定為低等級，則第二階段的深入評估則可以免除。倘若地震災害不容易透過快速篩檢出，則需要再進行第二階段更深入的評估。而進行第二階段更詳細的評估需要更多的資訊，才能進行嚴謹的調查，並提出預估的災害發生後果。

基礎建設的易損性評估

對於橋梁設施在地震災害下的統計資料，一般使用一種稱為「指標法」的評估方式。而「指標法」的內容包含橋梁地震災害的等級，由結構易損度、地震區及工址的地質災害條件，加上社會經濟考量上，針對不同橋梁的重要性分級等因素作綜合考量。首先，將橋梁所在位置的易損度和災害程度找出，再經過橋梁功能的重要性（考慮社會及經濟造成的影響）予以微調。除此之外，還要再納入其他考量因素（贅餘性和非屬於結構條件的因素）之後，才得到最終耐震補強的決策。（Buckle, 1911；FHWA, 1995）這樣的分級有兩個部份，一是可量化的數據，一是質化的資訊。前者基於結構的易損度及工址的災害類別為決定因子，透過量化的數據以地震分級（橋梁排序）。而後者質化的結果，則以量化後資訊以橋梁的重要性、路網的通達性、非地震可影響的缺陷程度、殘餘壽命及其他相關的因素納入之後，作出的一個綜合的優選排序。

減災標準

地震設計

從最近幾個大規模的美國高速公路橋梁在地震之下的表現看來，良好的設計細節是使得許多橋梁免去上部結構滑落或是橋柱剪力破壞的關鍵。經過過去 30 年的經驗，橋梁耐震設計已經成功地演進，並且逐漸發展出影響橋梁在地震和其他各類災害影響之下，仍能維持某種功能的細節。而耐震設計也在歷經多次的毀滅性地震及持續不斷地相關研究下，穩定地改進中。

現在由美國國家州政府交通官員協會（AASHTO）在 1992 年所頒佈的地震設計規範成為各州設計橋梁的根據。這套規範乃是由各州橋梁管理單位，含聯邦政府高速公路管理局（FHWA）及加州交通建設廳（CALTRANS）所聯合制訂的。經過 1971 年聖佛南多地震之後，使橋梁設計規範第一次納入災害考量而更加務實。而現今的橋梁設計基本目標，則演進到以防止橋梁在大規模地震力影響下，能夠免於發生落橋為設計的主要目標。並且在中度及輕微地震中，橋梁設計規範則以結構之構件維持在彈性變形的範圍之內，並且沒有造成嚴重損壞為原則目標。一旦發生大規模的地震，橋梁耐震設計雖以保持每一跨或任何跨的一部份構件都不會崩塌為目標，但是 AASHTO 設計規範僅允許某種程度可以修復的損壞為限制，例如：橋墩墩柱有限度的撓曲點的存在，並且最好限制結構預期的損害發生在地表之上，目的是容易在災害發生之後，以目視方法作檢查，並且容易快速復原。

Under the AASHTO's newly adopted seismic design guide specifications, the seismic performance objective is life safety (no collapse) based on a one-level rather than two-level design approach. This single level design criterion is based on a 5% probability of exceedance in 50 years (1000-year return period event). Higher performance levels (such as the operational objectives) may be used with the authorization of the bridge owners; however, these provisions do not provide guidance beyond the one-level approach.

Seismic Retrofitting

Bridges constructed according to newer design codes, in general, respond better to large earthquakes than those built using current codes. By now, it is well known that about 65% of the 600,000 highway bridges in the U.S. were constructed prior to 1971, with little or no consideration given to seismic forces. These bridges are very vulnerable to earthquake strikes, and need to be retrofitted based on seismicity and structural types. Toward this end, FHWA has issued several publications. Seismic Retrofitting Guidelines for Highway Bridges was first issued in 1983, and was followed in 1987 by Seismic Design and Retrofitting for Highway Bridges. In 1995, FHWA updated these manuals with more current knowledge and practical technology. In 2006, FHWA published two volumes Seismic Manual of Highway Structures, including Bridges and other Structures.

FHWA New Seismic Retrofitting Manual

Retrofitting is the most common method of mitigating risks; however, its cost may be so prohibitive that abandoning the bridge (total or partial closure with restricted access) or replacing it altogether with a new structure may be preferred. Alternatively, doing nothing and accepting the consequences of damage is another possible option. The decision to retrofit, abandon, replace, or do-nothing requires that both the importance and degree of vulnerability of the structure be carefully evaluated. Limited resources will generally require that deficient bridges be prioritized, with important bridges in high risk areas being given the first priority for retrofitting.

This manual contains procedures for evaluating and upgrading the seismic resistance of existing highway bridges. Specifically, it contains:

- A screening process to identify and prioritize bridges that need to be evaluated for seismic retrofitting.

- A methodology for quantitatively evaluating the seismic capacity of a bridge and determining the overall effectiveness of alternative retrofitting measures, including cost and ease of installation.

- Retrofit approaches and corresponding techniques for increasing the seismic resistance of existing bridges.

This process is illustrated in Figure 2. A bridge may be exempt from retrofitting if it is located in the lowest seismic zone, or has limited remaining useful life. Temporary bridges and those closed to traffic, may also be exempt.

在 AASHTO 最新制訂的設計規範中，強調於橋梁第一階層設計地震下仍表現出安全（無崩塌），第一階層設計是以 500 年回歸期內出現 5%機率以上的地震力為基礎（即 1,000 年回歸期計算的事件）。各橋梁主管機關可視實際情況的需要，訂定出更高的功能表現的要求（例如:可營運的目標）。但是，當前的設計規範並未明文指引，超過第一階層以上的設計原則。

耐震補強

以新版設計規範所建造的橋梁，一般而言，比起以過去舊規範所設計的橋梁，展現出對大規模地震更佳的耐震性能。截至今日為止，眾所周知在美國約有 60 萬座橋，而其中在 1971 年建造完成的橋數佔總體的 65%，這些老舊橋梁都在過去設計時，並不納入、或是僅僅少部分納入地震作為設計的考量因子。而這些過去建造的橋梁都暴露在地震災害的損害疑慮中，需要考量地震，並依結構型式加以進行耐震補強。針對這些老舊橋梁，FHWA 出版許多著作加以探討。第一版的橋梁耐震補強設計指引過去於 1983 年問世，隨後在 1987 年出版了高速公路橋梁地震設計及補強手冊。隨後經過 1995 年 FHWA 納入更新的研究和實務的技術，出版了修訂版，最近的一次出版是在 2006 年，FHWA 將內容更加充實而以兩冊發行，分別涵蓋高速公路結構地震設計及其他所屬構造。

新版 FHWA 耐震補強手冊

補強是減災最常見的一種方法，但是因為成本考量，往往只有限制改變功能（將原橋全部封閉或是限制出入）或是原地重建兩個比較優先的選項。同時完全將既有結構以不作任何補強，並選擇接受地震所遭到的可能破壞，也常常納入成為一種可行的方案之一。無論是補強、放棄、重建或是不作任何補強等決策，都需要同時考量橋梁功能的重要性及結構易損的程度。基於政府有限的預算，需要在許多補強的橋梁中找出優先順序，而又以在高風險地震區域內的重要橋梁為優先補強的目標。

新版的補強手冊內含如何針對既有的高速公路橋梁進行評估和升級為重點，特別是手冊中包含：

- 一套篩選的過程，將需要耐震補強的既有橋梁列出來並且排定優先次序。
- 一套既有橋梁耐震能力可量化的評估方法，並且針對不同補強方案，依照成本和施工容易度進行效益的總體評估。
- 補強設計工法及相關配套技術以有效提升既有橋梁的耐震性能。

圖 2 展示這些步驟的流程，凡在最低地震區域內的橋梁，或是該橋儘在有限的使用年限，可免除補強的考量，至於臨時通車的便橋或是已經封閉的橋梁可免於補強的評估。

This manual does not prescribe rigid requirements as to when and how bridges are to be retrofitted. The decision to retrofit a bridge depends on a number of factors, several of which are outside the realm of engineering. These include, but are not limited to, the availability of funding and a number of political, social, and economic issues. This manual focuses on the engineering factors.

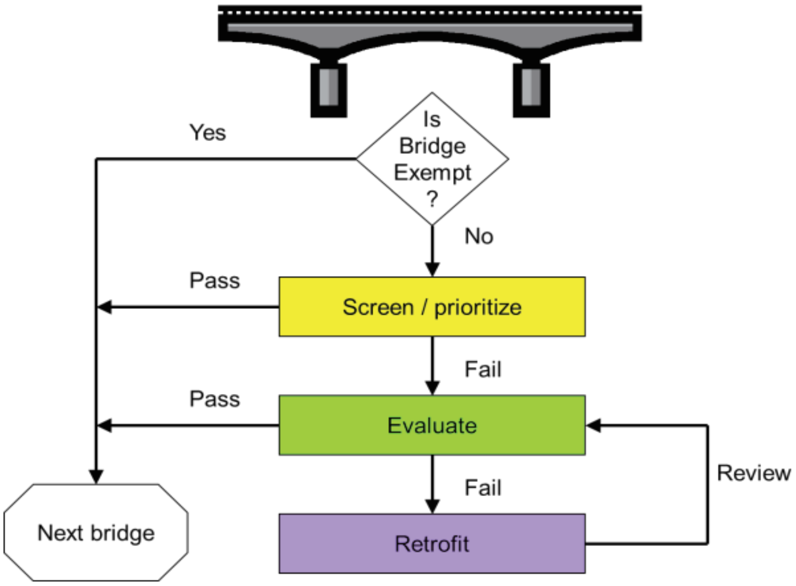

Figure 2. Overview of the retrofitting process for highway bridges.

Risk Analysis and Loss Estimations

Earthquakes are inevitable natural hazards with the potential for large numbers of fatalities and injuries, major property and infrastructure damage and serious disruption of everyday life. However, earthquake losses may be reduced to the minimum through a systematic risk assessment process. This has been recently recognized as a methodology of “Risk Management”, a process of determining what should be done for a hazard, deciding which hazards and at what scale magnitude should be managed, and in what priority order.

Effects of earthquake damage to highway components (e.g., bridges, tunnels, roadways, etc.) can go well beyond life-safety risks and costs to repair the damaged components. Such damage can also disrupt traffic flows which, in turn, can impact the region’s economic recovery and emergency response. These impacts will depend not only on the seismic performance of the components, but also on the characteristics of the overall highway system such as its network configuration and roadway-link characteristics (e.g., link locations, redundancies, and traffic capacities) with the GPS locations.

Unfortunately, such traffic impacts are usually not considered in seismic risk reduction activities at state transportation departments. One reason for this has been the lack of a technically-sound and practical tool for estimating these impacts. Therefore, since the mid-1990s, the FHWA has sponsored multi-year seismic-research projects that have included development and programming of such a tool. This has led to new software named REDARS (Risks from Earthquake DAmage to Roadway Systems) that was released for public use in March 2006.

這本手冊並不嚴格地明訂補強的時間點或是強制任何的補強工法，因為橋梁補強的決策是由數個考慮因子所決定，其中有許多是屬於非工程領域的因素，例如：資金充裕的程度，各類政治、社會和經濟的考量等等。而本手冊僅以工程考量為出發點。

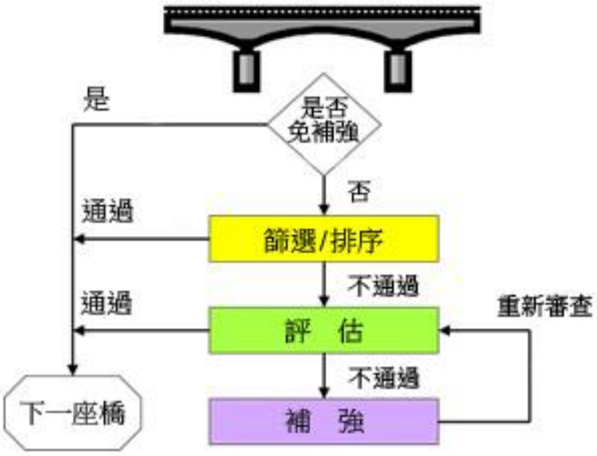

圖 2.高速公路橋梁補強步驟的篩選流程圖

風險分析及損失預估

地震為難以避免的天然災害，常導致大量人員傷亡和重大財務損失，並且對基礎建設和人民生計產生嚴重的影響，但是透過系統性風險評估步驟，可以將地震災損降到最低的程度。這個觀念已在「風險管理」相關方法中成為顯學，並強調對付何種災害時應當採取何種行動，且在某種災害中定位以何種優先順序來管理那種規模的災害。

地震對於高速公路附屬設施（如：橋梁、隧道、道路等）破壞的影響可能遠超過生命安全考量，且不是僅僅計算結構物損壞後的修復成本。好比對於交通中斷常常造成一個地區在經濟活動的復原，甚至救災工作的成效等，地震破壞的影響規模可能更大。而這些影響不只是取決於交通設施在地震影響下的反應，同時也在乎高速公路路網的佈設，以及其他道路的聯接性（意即:聯外道路的樞紐點，道路四通八達的贅餘度，和路網交通承載量）。

遺憾地是，在許多州的交通部門對於地震風險減量的各類計畫中，缺乏對於交通衝擊所造成影響的重視。造成這樣現象的原因，常常是因為缺乏技術成熟和實務的工具，以致無法對此類衝擊作出正確的評估。有鑑於此，FHWA 已經從 1990 年代中期，即展開投入多年期相關的地震研究工作，致力於發展出一套可用的評估管理工具，這些研究目前已經初步完成一套稱為 REDARS 的地震對公路損害的風險管理系統，並在 2006 年 3 月首度公開。

REDARS is a multi-disciplinary tool for seismic risk analysis (SRA) of highway systems nationwide. For any given earthquake, REDARS uses state-of-knowledge models to estimate: (a) the seismic hazards (ground motions, liquefaction, and surface fault rupture) throughout the system; (b) the resulting damage states (damage extent, type, and location) for each component in the system; and (c) how each component's damage will be repaired, including its repair costs, downtimes, and time-dependent traffic states (i.e., its ability to carry traffic as the repairs proceed over time after the earthquake). REDARS incorporates these traffic states into a highway-network link-node model, in order to form a set of system-states that reflect the extent and spatial distribution of roadway closures at various times after the earthquake. Then, REDARS applies network analysis procedures to each system-state, in order to estimate how these closures affect system-wide travel times and traffic flows. Finally, REDARS estimates corresponding economic losses and increases in travel times to/from key locations or along key lifeline routes. These steps can be applied for single earthquakes and no uncertainties (deterministic analysis) or for multiple earthquakes and simulations in which uncertainties in earthquake occurrence and in estimates of seismic hazards and component damage are considered (probabilistic analysis).

THE IMPACT FROM RECENT LARGE EARQUAKES

The recent huge earthquakes in China, Haiti and Chile have brought the big challenges to the earthquake engineering communities around the world. The large intensities of peak ground accelerations and much longer duration of shaking have brought to much greater difficulty in design and retrofitting of our highway bridges. FHWA's Seismic Research Program is working with seismic active States in the US as well as with other leading countries in the earthquake engineering, including Japan, Italy, China, Turkey, Chile and Taiwan, for the cooperation in exchanging technical information and collaborating in mutual interested research tasks.

FHWA is working with Multi-disciplinary Center of Earthquake Engineering Research (MCEER) of New York State University at Buffalo and University of Nevada at Reno (UNR) to initiate two major seismic research studies and started in 2007 to face the challenge of increase of traffic demand and seismic resilience of the highway infrastructure. The following are the summary of these two new studies:

The Innovative Technologies and Their Applications to Enhance the Seismic Performance of Highway Bridges

The objective of this study is to improve the seismic resistance of our highway system, by developing new innovative technologies and their applications, by developing cost-effective methods for implementing design and retrofitting technologies, and by refining and expanding applicability.

REDARS 是一套跨領域的全國性公路系統地震風險分析的工具，只要輸入任何的地震資料，REDARS 以最尖端的技術評估:(1)地震災害（包含：地表運動、土壤液化及地表破壞)；(2)對於受災的州（災害的程度、種類及地區）其公路系統的任何一個部份；(3)任何災損所需要修復的工法，包含修復所需之經費估算，系統封閉的時間長短，和那些州在道路封閉造成交通量影響的時間（意即:各地區地震發生之後，在進行搶通時能夠提供的運輸量)。REDARS 系統自動地將這些因地震造成交通量變化衝擊的州際公路，轉換成運輸網樞紐模式，並且計算出在地震發生之後，許多可能會封閉的道路系統，並在時空的變化下，各自因其他道路維修所產生的流量變化。隨後 REDARS 系統運用網路分析程式，估計出道路系統因為封閉所產生的運輸量和所耗費的運輸時間。最後 REDARS 可以估計出相對造成在經濟上的損失，並且因為災損所延長的物流時間。這些估算過程適用於一次性的地震，並且全部在確認的環境下，或是多筆地震災害下，許多未知的狀況進行模擬，使用機率方式運算出地震所造成的災害損失，並假設各類系統內設施損壞的許多不確定性。

近年大型地震的影響

近年來在中國、海地和智利所發生大規模的地震，對於全世界的地震工程界造成了不少的衝擊，正因為許多強烈地震所產生的地表加速度和更長時間的地表運動，使得美國在高速公路橋梁的地震設計及耐震補強工作更顯得有挑戰性。FHWA 的地震研究工作除了和許多美國境內許多地震發生頻繁的州不斷合作之外，近年來，也不斷地加強和許多在地震工程領域研究具有獨到成效的國家，如：日本、義大利、中國、土耳其、智利和臺灣，進行各類的合作和交流。

FHWA 同時也和紐約州立大學水牛城分校的「跨領域地震工程研究中心」（MCEER）及內華達州立大學雷諾校區（UNR）啟動了兩項主要的地震研究項目，並自 2007 年起開始著手研擬高速公路系統，因為地震災害所引起交通運量增加的需求及系統的恢復韌性，接下來便是針對這兩項研究成果所作總結的介紹。

高速公路橋梁地震下表現提昇的創新技及其應用

這項研究的宗旨在於改善既有高速公路系統對於地震的震能力，透過發展出創新研發的技術及應用，並兼顧耐震設計的成本，而更改善並擴大其可運用性。

This project is to increase the mobility and safety of our surface transportation system as the FHWA envisions reducing the construction/ maintenance time of new and existing highway structures. Applying accelerated bridge construction technology to high seismicity area requires more advanced connection detail to accommodate the large ground motions. Innovative technologies and their applications are continuously sought to refine and expand their applicability to enhance the seismic performance of our surface transportation system. The major tasks of this study are: Developing Detailed Technology to Apply Accelerated Bridge Construction (ABC) in Seismic Regions and Innovative Seismic Protection Technologies.

Improving the Seismic Resilience of the Federal-Aid Highway System

As life-safety is no longer the sole requirement for the successful design of a highway system for a major earthquake. Resilience is now expected by the traveling public as an integral component of any design strategy, so as to ensure rapid recovery and minimal impact on the socio-economic fabric of modern society. This realization has led to the concept of performance-based seismic design which is a relatively new development in the design and construction of civil infrastructure. Nevertheless substantial progress has been made in this area, particularly with respect to the performance of individual components of the built environment, such as buildings and bridges. But the real potential for performance-based design comes when these concepts are applied to systems and subsystems of the infrastructure, such as transportation networks, subject to both service load conditions and extreme events.

Performance measures calculated by REDARS include congestion and delay times. These measures allow system-level performance criteria to be specified for earthquakes of various sizes, such as maximum permissible traffic delay times and minimum restoration times. Accordingly the resilience of a highway system may be defined and measured in quantitative terms, such as the time it takes to restore the system’s pre-earthquake capacity, as illustrated in Figure 4.1. In doing so, financial and societal incentives can be developed that will improve resilience and at the same time reduce risk to life and property.

這項計劃正因為FHWA意識到縮減對既有橋梁的養護維修和新建橋梁的建造時間，將相對提高道路的機動性和安全性。在強震風險地區，推廣橋梁建設的加速工法，需要特別關注在樞紐點對於容許大規模地表錯動所必要的細節。當前許多這方面的創新技術和推廣仍在不斷地調整，並在各地震區域內公路運輸的系統中，透過應用這些技術提升結構的耐震性能。這項計畫最核心的工作就是不斷地研發各種設計細節，以致於能適用於地震區域內使用加速橋梁施工法及創新的地震防護技術。

改善由聯邦政府出資興建高速公路系統的耐震韌性

當前在大規模地震的影響下，生命安全已不是一個高速公路系統設計唯一關注的必要條件。就好比災後能夠迅速復原通車，並以減少對現代社會經濟因地震所產生的衝擊一樣，高速公路系統對震後復原的韌性，已經是許多社會大眾使用公共交通建設所預期的一環。這樣的思維，也是造就了近幾年對於基礎建設在設計和施工上，朝向注重功能表現的新發展。雖然至今這樣的趨勢已經明確地在建築和橋梁的許多細節上，產生重大的突破和進步；但是注重功能表現的設計，真正最具潛力的應用，是發揮在整體基礎建設的系統功能和分項系統之中，就好比交通運輸網路，面臨著日常承載及極端事件下，不同程度的影響條件。

透過REDARS系統所規劃出功能介訂的指標下，其中包含道路擁塞和造成延遲的時間。這些在系統功能表現所定義的標準，產生不同規模地震的設定值影響下，將可推估出最大容許道路因擁塞而造成的延遲時間，及最短容許恢復通車復原的時間。依據可量化的方式，便可具體地將耐震韌性定義出來，意即:公務單位需要將災損之後的系統，回復到災前原本運輸量所需要的時間，耐震韌性的定義如圖3所示。如此一來，便能加強社會大眾各界朝向關注在提升公路系統耐震韌性的動機，不僅只是注重降低地震造成對生命及財產損失的風險上。

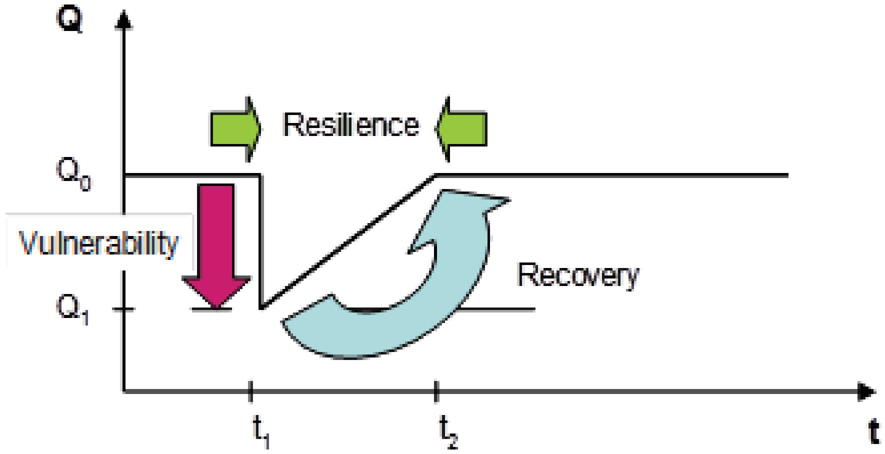

Figure 4.1. System resilience, after Bruneau (Buckle and Lee, 2006).

Whereas REDARS is the result of a decade-long period of development, and recently shown to adequately replicate the performance of the highway system in the San Fernando Valley following the 1995 Northridge earthquake, there is still much to be done to enable the methodology to be used with confidence and be widely applicable. REDARS has been developed with the expectation that new and more sophisticated modules will be developed overtime, in order to improve its accuracy and expand its range of application. This is considered a critical step in the drive towards quantifying the resilience of the highway system.

The objective of this project is to study the resilience of highway systems with a view to improving the performance of these systems subject to major earthquakes. A comprehensive assessment tool to measure highway resilience shall be developed by improving current loss estimation technologies, such as REDARS; factors affecting system resilience will be identified such as damage-tolerant bridge structures and network redundancy; design aids for curved bridges and those structures in near-fault regions will be developed; new technologies will be developed for improving the seismic performance of bridges; methodologies and technologies developed herein will be implemented in REDARS to the extent practical; and outreach to improve seismic safety will be conducted.

CONCLUDING REAMRKS

Hazard mitigation methods to reduce earthquake losses need a great effort for development and implementation. The most difficulty with mitigating earthquake hazards is that earthquakes come without any notice. There is no way to accurately predict when an earthquake will occur, nor what its magnitude will be. Earthquakes are devastating, often resulting in a great number of deaths, injuries and extensive infrastructure damage. Losses will occur in just one or two minutes. Systematic approaches to evaluating earthquake risks, including direct and indirect losses such as economic impact, have become an important issue in our engineering community.

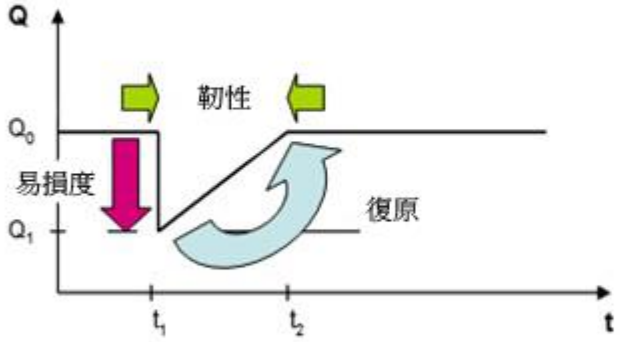

圖 3 高速公路系統韌性的定義(Buckle & Lee 2006)

即使 REDARS 系統歷經了數十年的研究成果，並且經最近的研究報告指出，透過複製 1995 年北嶺地震，成功地預測發生在聖佛南多谷的災情與真實狀況比較之後，證實系統的可靠。但是這個系統在推廣時，仍在確認社會大眾有信心及未來再納入其他的應用範圍上，確實仍有很大的進步空間。目前 REDARS 系統仍舊賦予著未來持續往更多創新和精緻的模組開發的方向發展，特別是在精準度的提昇和未來可應用的範圍上，將繼續不斷地發展，而這些方向都是高速公路系統耐震韌性定義在朝可量化的範圍發展十分關鍵的步調。

這個計畫的終極目標，就是在大規模地震影響之下，高速公路系統在韌性功能表現的提昇。透過一套完整的評估工具，首先發展出改善當前對災損的估計系統，就像是剛介紹的 REDARS。接下來一步，便是找出影響公路系統災害韌性的因子，好比耐震性能容許程度高的結構型態及公路路網的贅餘性，接著還需要發展出在近斷層地區各類曲線橋及所有結構的設計輔助資料，並且持續研發出能夠提昇橋梁耐震性能的新技術。這些內容也將都是未來在 REDARS 系統內持續鎖定預備囊括的科技和方法，而這套系統最終的實際成果，將會是大幅地改善地震災害之下的社會安全。

總結

對於降低地震災損的各類減災方法，都需要投注長期的發展和導入，對於地震災害這類沒有預警的天然災害尤其如此。正因為沒有任何方法可以精確地預測地震在何時發生，更無法估計一旦發生後所產生的規模，不可否認地震常是破壞力極大、常常造成大量生命的喪失、人員的傷亡和基礎建設的破壞，而且都發生在瞬時之間，因此對於工程界而言，有系統地評估各類地震所造成的災損，無論是直接成本，或是像對社會經濟造成衝擊的間接成本的估計，都應該是等量其觀的重要課題。

Since 1992, US Dept. of Transportation initiated a series of comprehensive seismic research studies targeted on retrofitting, design and risk analysis issues, and have produced many national applicable seismic retrofitting manuals, design and risk analysis tools. The FHWA is working closely with AASHTO and NEHRP agencies to mitigate the earthquake hazard and reduce the earthquake loss. This is indeed running against the time to implement all possible measures to enhancing our highway infrastructure safety and mobility even with the challenges of earthquake hazard.

REFERENCES

AASHTO(2008) Bridge Seismic Design Guide Specifications, published in June 2008, AASHTO, Washington, DC, USA

Buckle and Lee (2006), Seismic System Resilence, FHWA Seismic Research Project, McLean, VA.

FHWA (2006) Seismic Retrofitting Manual for Highway Structures – part I Bridges, FHWA-HRT-06-032, Mclean, VA.

REDARS 2(2006): Methodology and Software for Seismic Risk Analysis of Highway Systems, MCEER Publication in 2006, Buffalo, NY.

自西元1992年美國交通運輸主管機關即展開了一系列對於耐震補強、結構設計和風險分析等完整的地震工程相關研究，並且發展了許多適用於耐震補強的手冊，及使用於設計和分析之用的工具。FHWA緊密地和AASHTO及NEHRP兩個單位攜手合作，共同為舒緩地震的災害，並且降低震災的各類損失而努力。就像是在和時間賽跑一樣，為了提昇公路系統的安全性及流通性，在不斷地受到地震危害的威脅之下，需要加快步伐，將各類可能投入的工具導入在工程應用上。

參考書目

AASHTO(2008) Bridge Seismic Design Guide Specifications, published in June 2008, AASHTO, Washington, DC, USA

Buckle and Lee (2006), Seismic System Resilence, FHWA Seismic Research Project, McLean, VA.

FHWA (2006) Seismic Retrofitting Manual for Highway Structures – part I Bridges, FHWA-HRT-06-032, Mclean, VA.

REDARS 2(2006): Methodology and Software for Seismic Risk Analysis of Highway Systems, MCEER Publication in 2006, Buffalo, NY.