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Seismic Retrofit Practice

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40.1 Introduction

Until the 1989 Loma Prieta earthquake, most of the United States had not been concerned with seismic design for bridges, although some 37 states have some level of seismic hazard and there are hundreds of bridges in these other states that have been designed to seismic criteria that are not adequate for the seismic forces and displacements that we know today. Recent earthquakes, such as the 1971 San Fernando, California; the 1976 Tangshan, China [3]; the 1989 Loma Prieta, California; the 1994 Northridge, California; and the 1995 Hyogo-ken Nanbu (Kobe), Japan, have repeatedly demonstrated the seismic vulnerability of existing bridges and the urgent need for seismic retrofit.

The California Department of Transportation (Caltrans) owns and maintains more than12,000 bridges (spans over 6 m) and some 6000 other highway structures such as culverts (spans under 6 m), pumping plants, tunnels, tubes, highway patrol inspection facilities, maintenance stations, toll plazas, and other transportation-related structures. There are about an equal number on the City and County systems. Immediately after the February 9, 1971 San Fernando earthquake, Caltrans began a comprehensive upgrading of their *Bridge Seismic Design Specifications,* construction details, and a statewide bridge seismic retrofit program to reinforce the older non-ductile bridges systematically.

The success of the bridge seismic design and retrofit program and the success of future seismic design for California bridges is based, to a large degree, on the accelerated and "problem-focused" seismic research program that has provided the bridge design community with the assurance that the new specifications and design details perform reliably and meet the performance criteria. Caltrans staff engineers, consulting firms, independent peer-review teams, and university researchers have cooperated in this program of bridge seismic design and retrofit strengthening to meet the challenge presented in the June 1990 Board of Inquiry report [4].

This chapter discusses the bridge seismic retrofit philosophy and procedures practiced by the California bridge engineers. Issues addressed in this chapter can be of great benefit to those states and countries that are faced with seismic threats of lesser magnitude, yet have little financial support for seismic retrofitting, and much less for research and seismic detail development.

40.2 Identification and Prioritization

As part of any seismic retrofit program, the first phase should be to identify a list of specific bridges in need of retrofitting. That list of bridges also needs to be prioritized respecting which bridges pose the greatest risk to the community and therefore should be first to enter into a design phase in which a detailed analysis is completed and retrofit construction plans are completed for bidding.

In order to identify and prioritize a group of bridge projects, a type of coarse analysis must be completed. This analysis is carried out to expedite the process of achieving safety at the sites of the greatest risk. This analysis should not be confused with a detailed bridge system analysis conducted as part of the design phase. The process essentially identifies the projects that need to be addressed first. It should be recognized that it is not realistic to evaluate bridge systems to a refined degree in massive numbers simultaneously; however, it is quite possible to identify those bridges that possess the characteristics that have made bridges vulnerable, or at least more vulnerable, during past earthquakes. This coarse analysis is likely to be a collective review of databases of (1) bridge structural parameters that offer insight into the capacity of the systems to withstand earthquake loading and (2) bridge site parameters that offer insight to the potential for a site to experience threatening seismic motions. In case of many parameters to be evaluated, relative measures are possible. For example, if mass is recognized to be a characteristic that leads to poor behavior, then bridge systems can be compared quantitatively to their effective masses.

As the identification and prioritization process is well suited for high-speed computers, the process is vulnerable itself to being refined beyond its effective capacities. It is also vulnerable to errors of obvious omission because of the temptation to finalize the effort without appropriate review of the computer-generated results (i.e., never let a computer make a decision an engineer should make). The results should be reviewed carefully to check if they make engineering sense and are repeatable. In the Caltrans procedure, three separate experienced engineers reviewed each set of bridge plans and there had to be a consensus to retrofit or not. Common sense and experience are essential in this screening process.

40.2.1 Hazard

The seismic threat to a bridge structure is the potential for motions that are large enough to cause failure to occur at the bridge site. These measures of seismic threat eventually develop into the source of the demand side of the fundamental design equation. Such threats are characterized in numerous ways and presented in a variety of formats. One recognized method is to assume a deterministic approach and to recognize a single upper-bound measure of potential event magnitude for all nearby faults, assume motion characterizations for the fault sources, account for motion decay with distance from each fault, and characterize the motions at a site using a selected parameter such as spectral rock acceleration at 1 H. Alternatively, a probabilistic approach can be adopted that in a systematic manner incorporates the probabilities of numerous fault rupture scenarios and the attenuation of the motions generating the scenarios to the site. These motions then can be characterized in a variety of ways, including the additional information of a measure of the probability of occurrence. It is not economical to conduct a probabilistic ground motion study for each bridge. Size, longevity, and unusual foundations will generally determine the need.

Influences of the local geology at various sites are commonly accounted for employing various techniques. The motions can be teamed with the site response, which is often incorporated into the demand side, then called hazard. A hazard map is usually available in the bridge design specifications [1,2].

40.2.2 Structural Vulnerability

The vulnerability of a bridge system is a measure of the potential failure mechanisms of the system. To some degree, all bridge structures are ultimately vulnerable. However, judgment and reason can be applied to identify the practical vulnerabilities. Since the judgment is ideally based upon experience in observing field performances that are typically few in number, observing laboratory tests and considering/analyzing mechanisms, the judgment applied is very important and must be of high quality. Of these foundations upon which to base judgments, field observations are the most influential. The other two are more commonly used to develop or enhance understanding of the potential failure mechanisms.

Much has been learned about bridge performance in previous earthquakes. Bridge site, construction details, and structural configuration have major effects on bridge performance during an earthquake. Local site conditions amplify strong ground motions and subsequently increase the vulnerability of bridges on soft soil sites. The single-column-supported bridges were deemed more vulnerable because of lack of redundancy, based on experience in the 1971 San Fernando earthquake. Structural irregularity (such as expansion joints and C-bents) can cause stress concentration and have catastrophic consequences. Brittle elements with inadequate details always limit their ability to deform inelastically. A comprehensive discussion of earthquake damages to bridges and causes of the damage is presented in Chapter 34.

A designer's ability to recognize potential bridge system vulnerabilities is absolutely essential. A designer must have a conceptual understanding of the behavior of the system in order to identify an appropriate set of assumptions to evaluate or analyze the design elements.

40.2.3 Risk Analysis

A conventional risk analysis produces a probability of failure or survival. This probability is derived from a relationship between the load and resistance sides of a design equation. Not only is an approximate value for the absolute risk determined, but relative risks can be obtained by comparing determined risks of a number of structures. Such analyses generally require vast collections of data to define statistical distributions for all or at least the most important elements of some form of analysis, design, and/or decision equations. The acquisition of this information can be costly if obtainable at all. Basically, this procedure is to execute an analysis, evaluate both sides of the relevant design equation, and define and evaluate a failure or survival function. All of the calculations are carried out taking into account the statistical distribution of every equation component designated as a variable throughout the entire procedure.

To avoid such a large, time-consuming investment in resources and to obtain results that could be applied quickly to the retrofit program, an alternative, level-one risk analysis can be used. The difference between a conventional and level-one risk analysis is that in a level-one analysis judgments take the place of massive data supported statistical distributions.

The level-one risk analysis procedure can be summarized in the following steps:

1. Identify major faults with high event probabilities (priority-one faults)

Faults believed to be the sources of future significant seismic events should be identified by a team of seismologists and engineers. Selection criteria include location, geologic age, time of last displacement (late quarternary and younger), and length of fault (10 km min.). Each fault recognized in this step is evaluated for style, length, dip, and area of faulting in order to estimate potential earthquake magnitude. Faults are then placed in one of three categories: minor (ignored for the purposes of this project), priority two (mapped and evaluated but unused for this project), or priority one (mapped, evaluated, and recognized as immediately threatening). In California, this step was carried out by consulting the California Division of Mines and Geology and the recent U.S. Geological Survey studies.

2. Develop average attenuation relationships at faults identified in Step 1

3. Define the minimum ground acceleration capable of causing severe damage to bridge structures

The critical (i.e., damage-causing) level of ground acceleration is determined by performing nonlinear analyses on a typical highly susceptible structure (single-column connector ramp) under varying maximum ground acceleration loads. The lowest maximum ground acceleration that requires the columns providing a ductility ratio of 1.3 may be defined as the critical level of ground acceleration. The critical ground acceleration determined in the Caltrans study was 0.5 *g*.

4. Identify all the bridges within high-risk zones defined by the attenuation model of Step 2 and the critical acceleration boundary of Step 3

The shortest distance from every bridge to every priority-one fault is calculated. Each distance is compared to the distance from each respective level of magnitude fault to the critical ground acceleration decremented acceleration boundary. If the distance from the fault to the bridge is less than the distance from the fault to the critical acceleration boundary, the bridge shall be determined to lie in the high-risk zone and is added to the screening list for prioritization.

5. Prioritize the threatened bridges by summing weighted bridge structural and transportation characteristic scores

This step constitutes the process used to prioritize the bridges within the high-risk zones to establish the order of bridges to be investigated for retrofitting. It is in this step that a risk value is assigned to each bridge. A specifically selected subset of bridge structural and transportation characteristics of seismically threatened bridges should be prepared in a database. Those characteristics were ground acceleration; route type — major or minor; average daily traffic (ADT); column design single or multiple column bents; confinement details of column (relates to age); length of bridge; skew of bridge, and availability of detour.

Normalized preweight characteristic scores from 0.0 to 1.0 are assigned based on the information stored in the database for each bridge. Scores close to 1.0 represent high-risk structural characteristics or high cost of loss transportation characteristics. The preweight scores are multiplied by prioritization weights. Postweight scores are summed to produce the assigned prioritization risk value.

Determined risk values are not to be considered exact. Due to the approximations inherent in the judgments adopted, the risks are no more accurate than the judgments themselves. The exact risk is not important. Prioritization list qualification is determined by fault proximity and empirical attenuation data, not so much by judgment. Therefore, a relatively high level of confidence is associated with the completeness of the list of threatened bridges. Relative risk is important because it establishes the order of bridges to be investigated in detail for possible need of retrofit by designers.

A number of assumptions are made in the process of developing the prioritized list of seismically threatened bridges. These assumptions are based on what is believed to be the best engineering judgment available. It seems reasonable to pursue verification of these assumptions some time in the future. Two steps seem obvious: (1) monitoring the results of the design departments retrofit analyses and (2) executing a higher-level risk analysis.

Important features of this first step are the ease and cost with which it could be carried out and the database that could be developed highlighting bridge characteristics that are associated with structures in need of retrofit. This database will be utilized to confirm the assumptions made in the retrofit program. The same database will serve as part of the statistical support of a future conventional risk analysis as suggested in the second step. The additional accuracy inherent in a higher-order risk analysis will serve to verify previous assumptions, provide very good approximations of actual structural risk, and develop or evaluate postulated scenarios for emergency responses. It is reasonable to analyze only selected structures at this level. A manual screening process may be used that includes review of “as-built” plans by at least three engineers to identify bridges with common details that appeared to need upgrading.

After evaluating the results of the 1989 Loma Prieta earthquake, Caltrans modified the risk analysis algorithm by adjusting the weights of the original characteristics and adding to the list. The additional characteristics are soil type; hinges, type and number; exposure (combination of length and ADT); height; abutment type; and type of facility crossed.

Even though additional characteristics were added and weights were adjusted, the postweight scores were still summed to arrive at the prioritization risk factor. The initial vulnerability priority lists for state and locally owned bridges were produced by this technique and retrofit projects were designed and built.

In 1992, advances were made in the Caltrans procedures to prioritize bridges for seismic retrofit and a new, more accurate algorithm was developed. The most significant improvement to the prioritization procedure is the employment of the multiattribute decision theory. This prioritization scheme incorporates the information previously developed and utilizes the important extension to a multiplicative formulation.

This multiattribute decision procedure assigns a priority rating to each bridge enabling Caltrans to decide more accurately which structures are more vulnerable to seismic activity in their current state. The prioritization rating is based on a two-level approach that separates out seismic hazard from impact and structural vulnerability characteristics. Each of these three criteria (hazard, impact, and structural vulnerability) depends on a set of attributes that have direct impact on the performance and potential losses of a bridge. Each of the criteria and attributes should be assigned a weight to show their relative importance. Consistent with previous work, a global utility function is developed for each attribute.

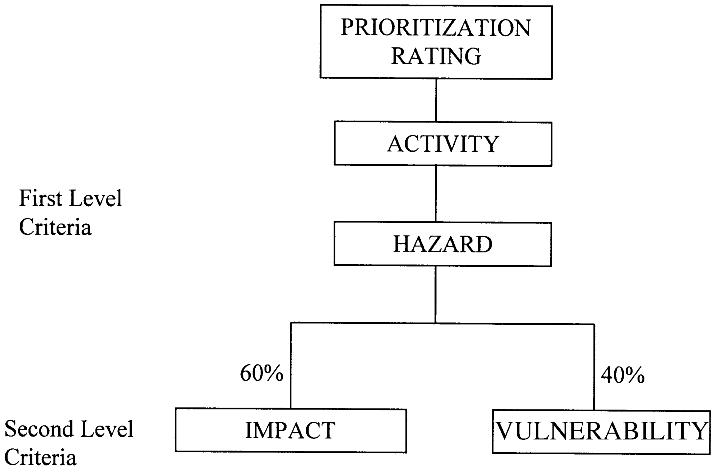
This new procedure provides a systematic framework for treating preferences and values in the prioritization decision process. The hierarchical nature of this procedure has the distinct advantage of being able to consider seismicity prior to assessing impact and structural vulnerability. If seismic hazard is low or nonexistent, then the values of impact and structural vulnerability are not important and the overall postweight score will be low because the latter two are added but the sum of those two are multiplied by the hazard rating. This newly developed prioritization procedure is defensible and theoretically sound. It has been approved by Caltrans Seismic Advisory Board.

Other research efforts [5–7] in conjunction with the prioritization procedure involve a sensitivity study that was performed on bridge prioritization algorithms from several states. Each procedure was reviewed in order to investigate whether or not California was neglecting any important principles. In all, 100 California bridges were selected as a sample population and each bridge was independently evaluated by each of the algorithms. The 100 bridges were selected to represent California bridges with respect to the variables of the various algorithms. California, Missouri, Nevada, Washington, and Illinois have thus far participated in the sensitivity study.

The final significant improvement to the prioritization procedure is the formal introduction of varying levels of seismicity. A preliminary seismic activity map for the state of California has been developed in order to incorporate seismic activity into the new prioritization procedure. In late 1992 the remaining bridges on the first vulnerability priority list were reevaluated using the new algorithm and a significant number of bridges changed places on the priority list but there were no obvious trends. Figure 40.1 and Table 40.1 show the new algorithm and the weighting percentages for the various factors.

40.3 Performance Criteria

Performance criteria are the design goals that the designer is striving to achieve. How do you want the structure to perform in an earthquake? How much damage can you accept? What are the reasonable



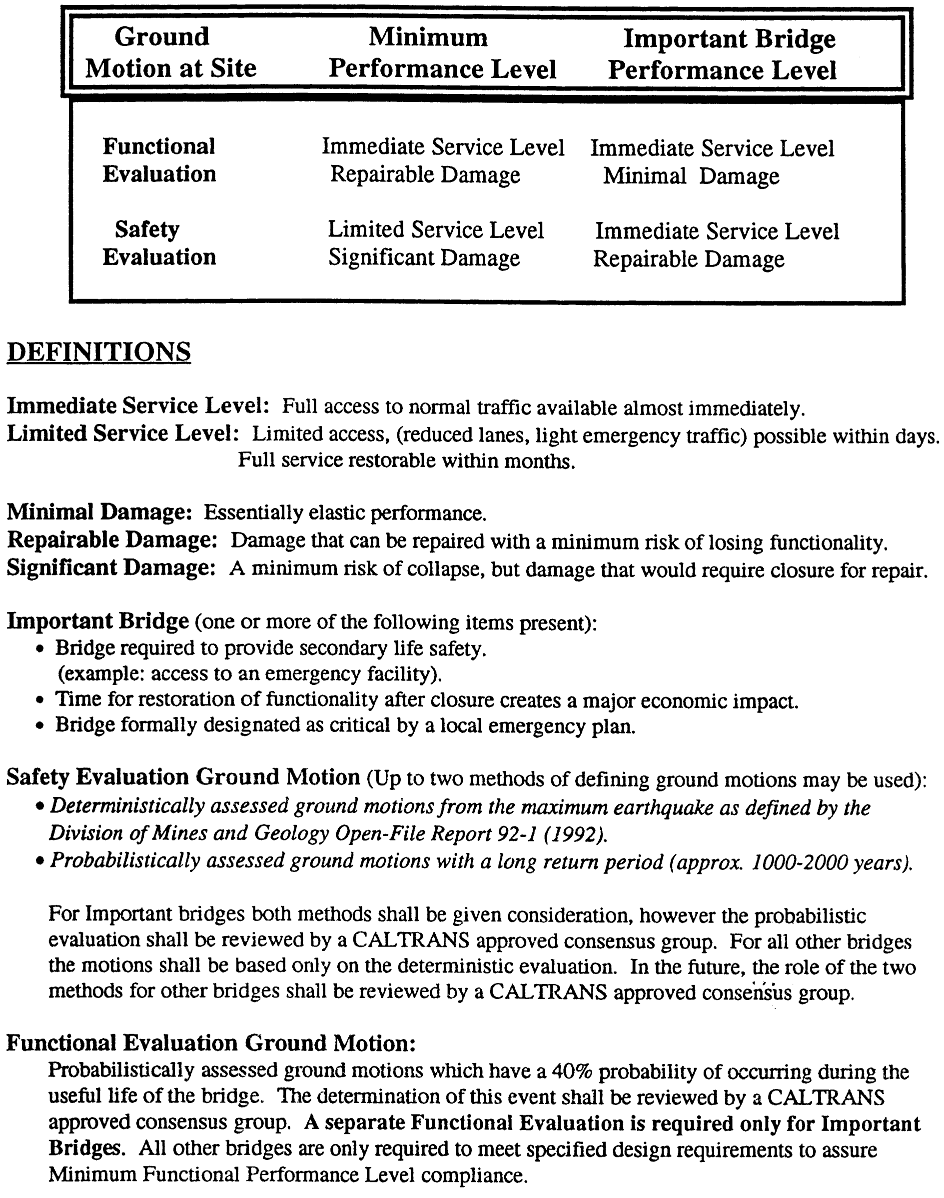
$$\begin{array}{rl}
\text{Prioritization Rating} & = \text{(Activity)(Hazard)[(0.6)(Impact) + 0.4(Vulnerability)]} \\
\text{Activity} & = \text{(Global Utility Function Value)} \\
\text{Hazard} & = \sum \text{(Hazard Attribute Weight) (Global Utility Function Value)} \\
\text{Impact} & = \sum \text{(Impact Attribute Weight) (Global Utility Function Value)} \\
\text{Vulnerability} & = \sum \text{(Vulnerability Attribute Weight) (Global Utility Function Value)}
\end{array}$$

FIGURE 40.1 Risk analysis — multiattribute decision procedure.

TABLE 40.1 Multi-attribute Weights

	Attributes	Weights (%)
Hazard	Soil conditions	33
	Peak rock acceleration	28
	Seismic duration	29
Impact	ADT on structure	28
	ADT under/over structure	12
	Detour length	14
	Leased air space (residential, office)	15
	Leased air space (parking, storage)	7
	RTE type on bridge	7
	Critical utility	10
	Facility crosses	7
Vulnerability	Year designed (constructed)	25
	Hinges (drop-type failure)	16.5
	Outriggers, shared column	22
	Bent redundancy	16.5
	Skew	12
	Abutment type	8

alternate routes? How do you define various levels of damage? How long do you expect for repair of various levels of damage? The form of the performance criteria can take many forms usually depending on the perspective and background of the organization presenting it. The two most common forms are functional and structural [Caltrans 1993]. The functional is the most appropriate form for the performance criteria because it refers to the justification of the existence of the structure. For example, the functional performance criteria of a bridge structure would include measures of post-earthquake capacity for traffic to flow across the bridge. Performance of the structure itself is more appropriately addressed with the structural design criteria. This would be codes, design memorandums, etc. An example of



Ground Motion at Site	Minimum Performance Level	Important Bridge Performance Level
Functional Evaluation	Immediate Service Level Repairable Damage	Immediate Service Level Minimal Damage
Safety Evaluation	Limited Service Level Significant Damage	Immediate Service Level Repairable Damage

DEFINITIONS

Immediate Service Level: Full access to normal traffic available almost immediately.
Limited Service Level: Limited access, (reduced lanes, light emergency traffic) possible within days. Full service restorable within months.

Minimal Damage: Essentially elastic performance.
Repairable Damage: Damage that can be repaired with a minimum risk of losing functionality.
Significant Damage: A minimum risk of collapse, but damage that would require closure for repair.

Important Bridge (one or more of the following items present):
- Bridge required to provide secondary life safety. (example: access to an emergency facility).
- Time for restoration of functionality after closure creates a major economic impact.
- Bridge formally designated as critical by a local emergency plan.

Safety Evaluation Ground Motion (Up to two methods of defining ground motions may be used):
- *Deterministically assessed ground motions from the maximum earthquake as defined by the Division of Mines and Geology Open-File Report 92-1 (1992).*
- *Probabilistically assessed ground motions with a long return period (approx. 1000-2000 years).*

For Important bridges both methods shall be given consideration, however the probabilistic evaluation shall be reviewed by a CALTRANS approved consensus group. For all other bridges the motions shall be based only on the deterministic evaluation. In the future, the role of the two methods for other bridges shall be reviewed by a CALTRANS approved consensus group.

Functional Evaluation Ground Motion:
Probabilistically assessed ground motions which have a 40% probability of occurring during the useful life of the bridge. The determination of this event shall be reviewed by a CALTRANS approved consensus group. **A separate Functional Evaluation is required only for Important Bridges.** All other bridges are only required to meet specified design requirements to assure Minimum Functional Performance Level compliance.

FIGURE 40.2 Seismic performance criteria for the design and evaluation of bridges.

what would be addressed in design criteria would be acceptable levels of strains in different structural elements and materials. These levels of strains would be defined to confidently avoid a defined state of failure, a deformation state associated with loss of capacity to accommodate functional performance criteria, or accommodation of relatively easy-repair.

Performance criteria must have a clear set of achievable goals, must recognize they are not independent of cost, and should be consistent with community planning. Figure 40.2 shows the seismic performance criteria for the design and evaluation of bridges in the California State Highway System [Caltrans 1993].

Once seismic performance criteria are adopted, the important issue then is to guarantee that the design criteria and construction details will provide a structure that meets that adopted performance criteria. In California a major seismic research program has been financed to physically test large-scale and full-sized models of bridge components to provide reasonable assurance to the engineering community that those details will perform as expected in a major seismic event. The current phase of that testing program involves real-time dynamic shaking on large shake tables. In addition, the Caltrans bridge seismic design specifications have been thoroughly reviewed in the ATC-32 project to ensure that they are the most up-to-date with state-of-the-art technology. On important bridges, project-based design criteria have been produced to provide guidance to the various design team members on what must be done to members to ensure the expected performance.

40.4 Retrofit Design

40.4.1 Conceptual Design

Design is the most-impacting part of the entire project. The conceptual design lays out the entire engineering challenge and sets the course for the analysis and the final detailed design. The conceptual design is sometimes referred to as type-selection or, in the case of seismic retrofit, the strategy. A seismic retrofit strategy is essentially the project engineer's plan that lays out the structural behavior to lead to the specified performance. The most important influential earthquake engineering is completed in this early phase of design. It is within this phase that "smart" engineering can be achieved (i.e., work smarter not harder). That is, type-selections or strategies can be chosen such that unreliable or unnecessary analyses or construction methods are not forced or required to be employed. When this stage of the project is completed well, a plan is implemented such that difficulties are wisely avoided when possible throughout not only the analysis, design, specification development, and construction phases, but also the remaining life of the bridge from a maintenance perspective. With such understanding, an informed decision can be made about which structural system and mechanisms should be selected and advanced in the project.

Highway multiple connector ramps on an interchange typically are supported by at least one column in the median of a busy functioning freeway. Retrofit strategies that avoid column retrofitting of the median columns have safety advantages over alternatives. Typically, columns outside the freeway traveled way can be strengthened and toughened to avoid median work and the problems of traffic handing.

On most two- and three-span shorter bridges the majority of seismic forces can be transferred into the abutments and embankments and thus reduce or entirely eliminate the amount of column retrofitting necessary. Large-diameter CIDH piles drilled adjacent to the wingwalls at abutments have been effective in resisting both longitudinal and transverse forces.

For most multiple-column bents the footing retrofits can be reduced substantially by allowing the columns to hinge at the bottom. This reduces the moments transferred into the foundations and lowers total costs. Sufficient testing on footing/pile caps and abutments has been conducted. It is found that a considerable amount of passive lateral resistance is available. Utilizing this knowledge can reduce the lateral force requirement of the structural foundations.

Continuity is extremely important and is the easiest and cheapest insurance to obtain. Well-designed monolithic structures also have the added advantage of low maintenance. Joints and bearings are some of the major maintenance problems on bridges today. If structures are not continuous and monolithic, they must be tied together at deck joints, supports, and abutments. This will prevent them from pulling apart and collapsing during an earthquake.

Ductility in the substructure elements is the second key design consideration. It is important that when you design for ductility you must be willing to accept some damage during an earthquake. The secret to good seismic design is to balance acceptable damage levels with the economics of preventing or limiting the damage. Properly designed ductile structures will perform well during an earthquake as long as the design has accounted for the displacements and controlled or provided for them at abutments and hinges. For a large majority of bridges, displacement criteria control over strength criteria in the design for seismic resistance.

FIGURE 40.3 Hinge joint restrainer.

40.4.2 Retrofit Strategies

Designers of bridge seismic retrofit projects acquire knowledge of the bridge system, develop an understanding of the system response to potential earthquake ground motions, and identify and design modifications to the existing system that will change the expected response to one that satisfies the project performance criteria. This is accomplished by modifying any or all of the system stiffness, energy absorption, or mass characteristics. These characteristics or behavior can commonly be grouped into all structural system types, such as trusses, frames, single-column bent, shear walls, CIDH systems. This section briefly discusses various seismic retrofit strategies used in California. Chapter 43 presents more-detailed information.

Hinge Joint Restrainers

Spans dropped off from too narrow support seats and separation of expansion joints were two major causes of bridge collapse during the 1971 San Fernando earthquake. The initial phase of the Caltrans Bridge Seismic Retrofit Program involved installation of hinge and joint restrainers to prevent deck joints from separating (Figure 40.3). Included in this phase was the installation of devices to fasten the superstructure elements to the substructure in order to prevent those superstructure elements from falling off their supports (Figure 40.4). This phase was essentially completed in 1989 after approximately 1260 bridges on the California State Highway System had been retrofitted at a cost of over $55 million.

Figure 40.5 shows the installation of an external hinge extender detail that is designed to prevent the supported section of the superstructure from dropping off its support. Note the very narrow hinge details at the top of this picture, which is common on the 1960s era bridges throughout California.

The Loma Prieta earthquake of October 17, 1989 again proved the reliability of hinge and joint restrainers, but the tragic loss of life at the Cypress Street Viaduct on I-880 in Oakland emphasized the necessity to accelerate the column retrofit phase of the bridge seismic retrofit program immediately with a higher funding level for both research and implementation [8].

Confinement Jackets

The largest number of large-scale tests have been conducted to confirm the calculated ductile performance of older, nonductile bridge columns that have been strengthened by application of

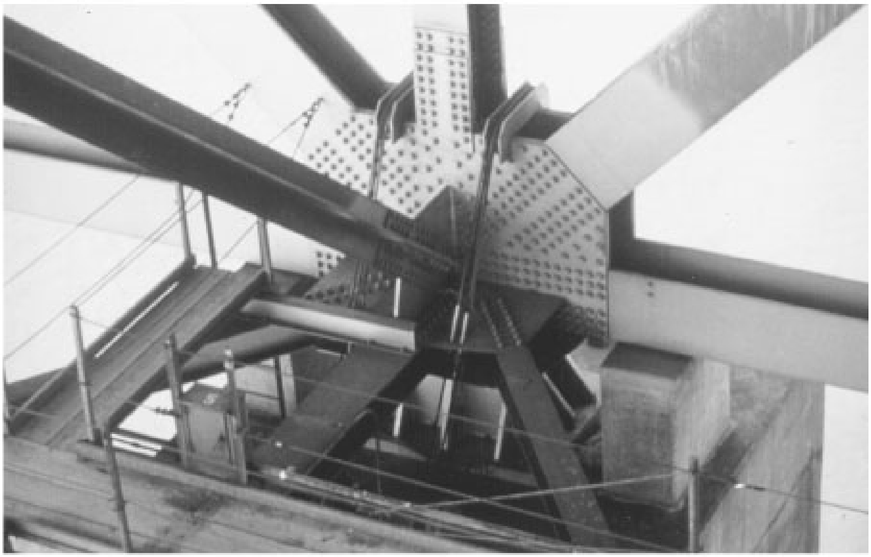


FIGURE 40.4 Hold down devices for vertical acceleration.

FIGURE 40.5 External hinge extenders on Santa Monica freeway structures.

structural concrete, steel plate, prestressed strand, and fiberglass-composite jackets to provide the confinement necessary to ensure ductile performance. Since the spring of 1987 the researchers at University of California, San Diego have completed over 80 sets of tests on bridge column models [9–14]. Figure 40.6 shows reinforcement confinement for a column retrofit. Figure 40.7 shows a completed column concrete jacket retrofit. Figure 40.8 is a completed steel jacket retrofit.

Approximately 2200 of California's 12,000 bridges are located in the Los Angeles area, so it is significant to examine the damage and performance of bridges in the Northridge earthquake of January 17, 1994. About 1200 of these bridges were in an area that experienced ground accelerations greater than 0.25 g and several hundred were in the area that experienced ground accelerations of

FIGURE 40.6 Reinforcement confinement retrofit.

0.50 *g*. There were 132 bridges in this area with post-San Fernando retrofit details completed and 63 with post-Loma Prieta retrofit details completed (Figure 40.9). All of these retrofitted bridges performed extremely well and most of the other bridges performed well during the earthquake; bridges constructed to the current Caltrans seismic specifications survived the earthquake with very little damage. Seven older bridges, designed for a smaller earthquake force or without the ductility of the current Caltrans design, sustained severe damage during the earthquake. Another 230 bridges suffered some damage ranging from serious problems of column and hinge damage to cracks, bearing damage, and approach settlements, but these bridges were not closed to traffic during repairs.

Link Beams

Link beams may be added to multicolumn bents to provide stiffener frame and reduce the unsupported column length. By using this development combined with other techniques, it may be possible to retrofit older, nonductile concrete columns without extensive replacement. Figure 40.10 shows link beams and installation of columns casings at the points of maximum bending and locations of anticipated plastic hinges on Santa Monica freeway structures. Half-scale models of these columns were constructed and tested under simulated seismic loading conditions to proof-test this conceptual retrofit design.

Ductile Concrete Column Details

Most concrete bridge columns designed since 1971 contain a slight increase in the main column vertical reinforcing steel and a major increase in confinement and shear reinforcing steel over the

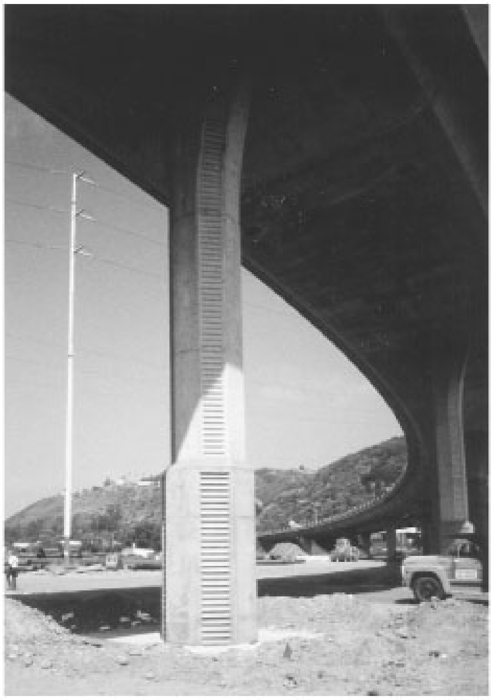


FIGURE 40.7 Concrete jacket column retrofit.

pre-1971 designs. All new columns, regardless of geometric shape, are reinforced with one or a series of spiral-wound interlocking circular cages. The typical transverse reinforcement detail now consists of #6 (¾ in. diameter) hoops or continuous spiral at approximately 3-in. pitch over the full column height (Figure 40.11). This provides approximately eight times the confinement and shear reinforcing steel in columns than what was used in the pre-1971 nonductile designs. All main column reinforcing is continuous into the footings and superstructure. Splices are mostly welded or mechanical, both in the main and transverse reinforcing. Splices are not permitted in the plastic hinge zones. Transverse reinforcing steel is designed to produce a ductile column by confining the plastic hinge areas at the top and bottom of columns. The use of grade 60, A 706 reinforcing steel in bridges has recently been specified on all new projects.

Concrete Beam–Column–Bent Cap Details

Major advances have been made in the area of beam–column joint confinement, based on the results of research at both University of California, Berkeley, and San Diego. The performance and design criteria and structural details developed for the I-480 Terminal Separation Interchange and the I-880 replacement structures reflect the results of this research and were reported by Cooper [15]. Research is continuing at both institutions to refine the design details further to ensure ductile performance of these joints.

The concept using an integral edge beam can be used on retrofitting curved alignments, such as the Central Viaduct (U.S. 101) in downtown San Francisco and the Alemany Interchange on U.S. 101 in south San Francisco. The proofing-testing program was reported by Mahin [1991]. The concept using an independent edge beam can be used on retrofitting straight alignments. Figure 40.12 shows a graphic schematic of the proposed retrofit technique and Figure 40.13 shows the field installation of the joint reinforcement steel. Figure 40.14 shows the completed structure after retrofitting for seismic spectra that reach more than 2.0 *g* at the deck level.

FIGURE 40.8 Steel jacket column retrofit.

For outrigger bent cap under combined bending, shear, and torsion, an improved detail of column transverse reinforcement is typically continued up through the joint regions and the joints are further confined for shear and torsion resistance. The details for these joints usually require 1 to 3% confinement reinforcing steel. Thewalt and Stojadinovic [16] of University of California, Berkeley reported on this research. Figure 40.15 shows the complex joint-reinforcing steel needed to confine these joints for combined shear, bending, and torsion stresses. Design of these large joints requires use of the strut-and-tie technology to account properly for the load paths through the joint.

Steel Bridge Retrofit

Despite the fact that structural steel is ductile, members that have been designed by the pre-1972 seismic specifications must be evaluated for the seismic forces expected at the site based on earthquake magnitudes as we know them today. Typically, structural steel superstructures that had been tied to their substructures with joint and hinge restrainer systems performed well. However, we have identified many elevated viaducts and some smaller structures supported on structural steel columns that were designed prior to 1972 and that will require major retrofit strengthening for them to resist modern earthquake forces over a long period of shaking. One weak link is the older rocker bearings that will probably roll over during an earthquake. These can be replaced with modern neoprene, Teflon, pot, and base isolation bearings to ensure better performance in an earthquake. Structural steel columns can be strengthened easily to increase their toughness and ability to withstand a long period of dynamic input.

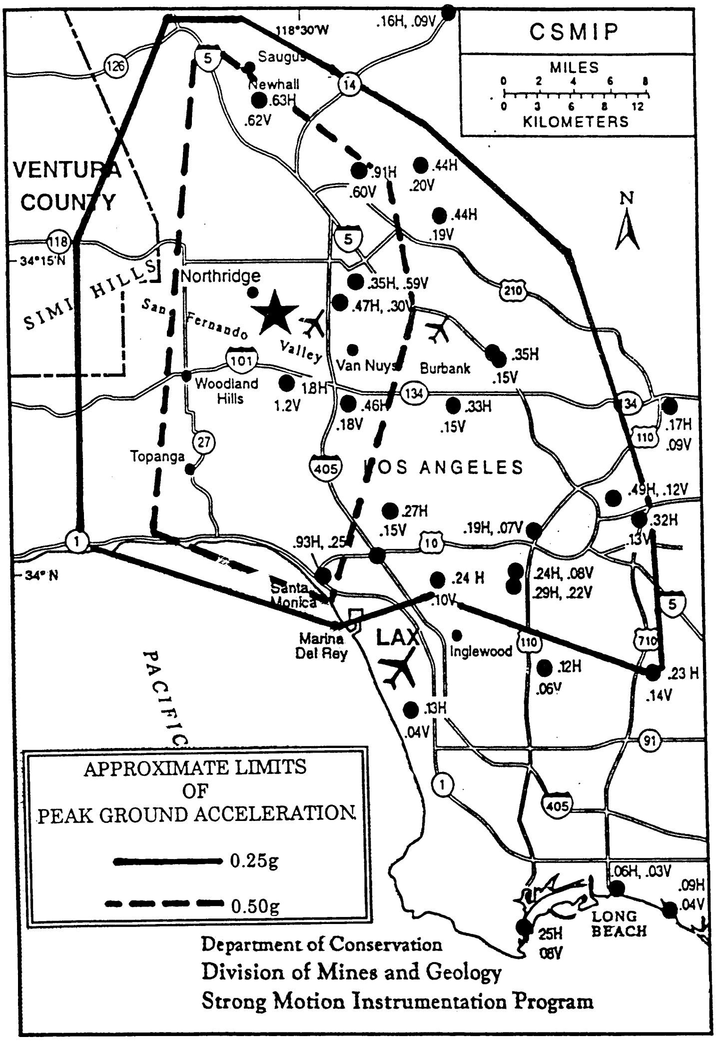


FIGURE 40.9 Peak ground acceleration zones — Northridge earthquake.

FIGURE 40.10 Steel jackets and bond beam — Santa Monica Freeway.

FIGURE 40.11 Column reinforcing steel cage.

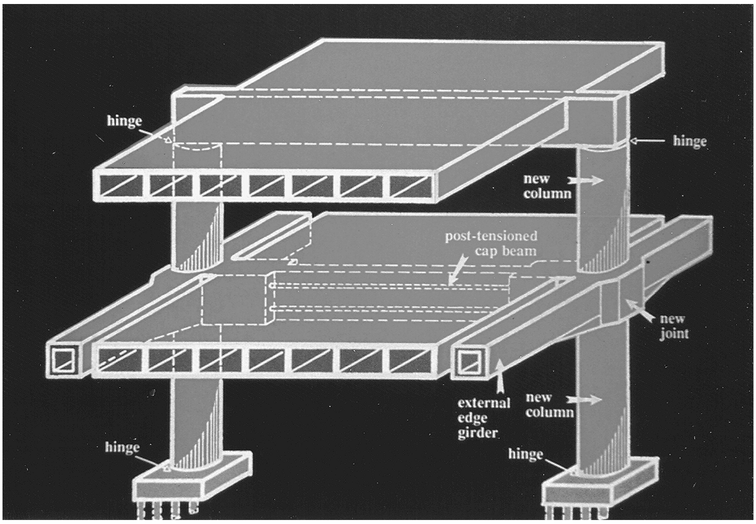


FIGURE 40.12 Graphic of edge beam retrofit scheme.

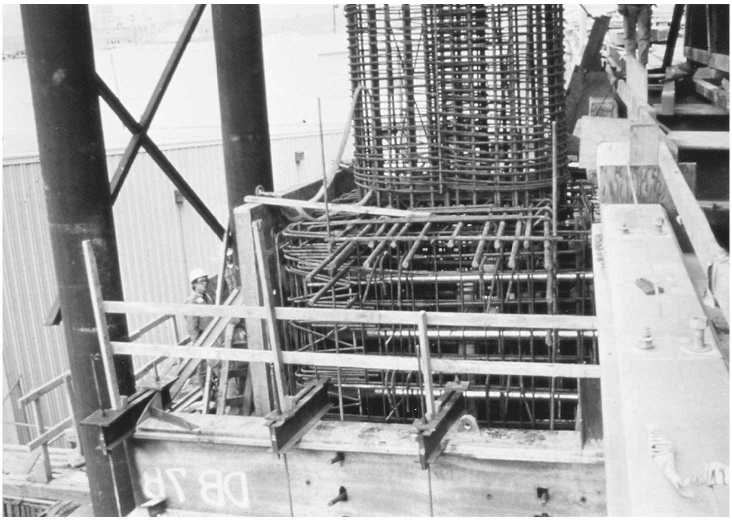


FIGURE 40.13 Field installation of joint reinforcing steel.

FIGURE 40.14 Completed retrofitted structures.

Footing and Pile Cap Modifications

Bridge column footing details established in 1980 consist of top and bottom mats of reinforcement tied together vertically by closely spaced hooked stirrups (Chapter 43). The column longitudinal rebars rest on the bottom mat, are hooked into the footing with hooks splayed outward, and are confined by spiral or hoop reinforcement between the mats. For pile foundations, the piles are reinforced and securely connected to the pile caps to resist the seismic tensile loads (Figure 40.16). The justifications for these details were widely debated, and strut-and-tie procedure seems to substantiate the need (Chapter 38). However, a proof-test of a footing with typical details performed adequately.

Seismic Isolation and Energy Dissipation Systems

Seismic isolation and supplemental energy dissipation devices have been successfully used in many bridge seismic design and retrofit projects. A detailed discussion is presented in Chapter 41. Extreme caution should be exercised when considering isolation devices. As discussed earlier, good, well-detailed, monolithic moment-resisting frames provide adequate seismic resistance without the

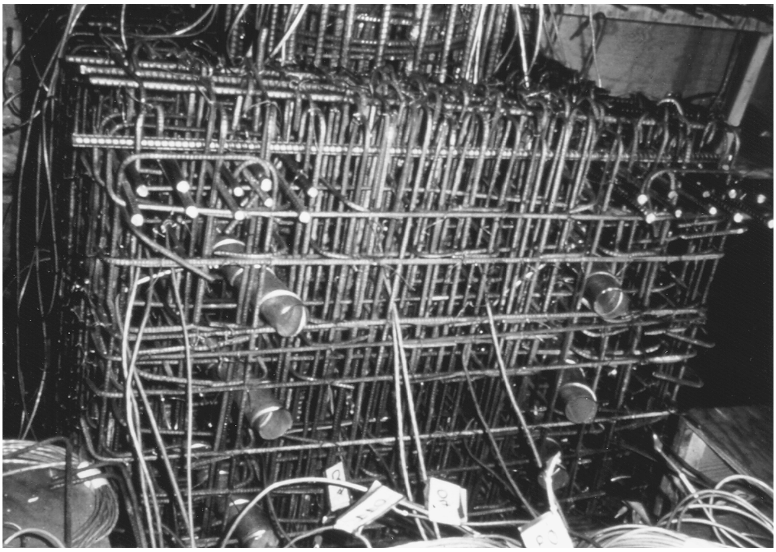


FIGURE 40.15 Reinforcing steel pattern in complex outrigger joint.

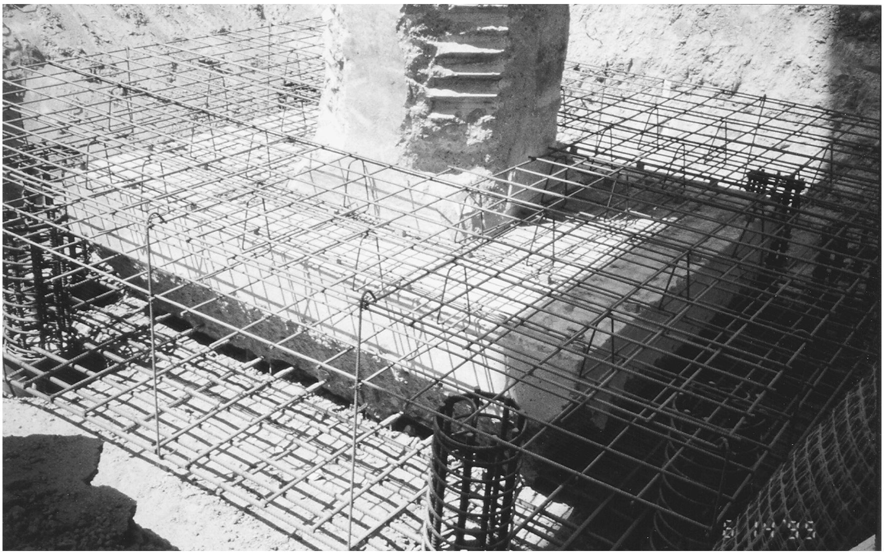


FIGURE 40.16 Typical footing and pile cap modification.

inherent maintenance problems and higher initial costs. These devices, however, are excellent for replacing older, rocker bearings.

40.4.3 Analysis

Analysis is the simulation of the structure project engineer's strategy of the bridge response to the seismic motions. A good seismic design is robust and as relatively insensitive to fluctuations in ground motions as possible. Quantitative analysis is the appropriate verification of the capacity of the system and its individual subsystems being greater than the recognized demand.

The more complicated the seismic strategy, the more complicated will be the analysis. If the behavior of the system is to be nearly elastic with minor damage developed, then the analysis is

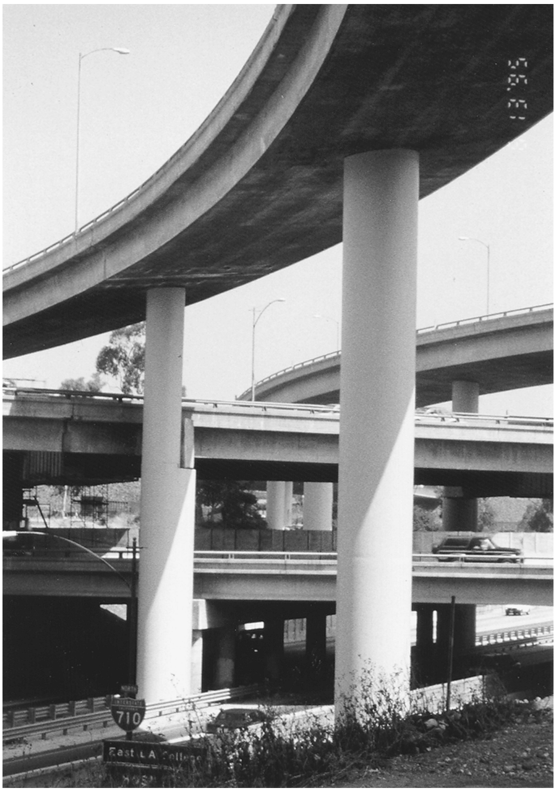


FIGURE 40.17 Completed seismic retrofit of I-5/710 interchange in Los Angeles.

likely to be simply linear-elastic analysis. However, if the behavior is likely to be complex, changing in time, with significant damage developed and loss of life or important facility loss, then the analysis is likely to be similarly complex.

As a rule of thumb, the complexity of the analysis shadows the complexity of the strategy and the importance of the bridges. However, it should be noted that a very important bridge that is being designed to behave essentially elastically will not require complex analysis. It should always be recognized that analysis serves design and is part of design. Analysis cannot be a separated form. Too many engineers confuse analysis with design. Good design combines the analysis with judgment, common sense, and use of tested details.

40.4.4 Aesthetics

The design approach to bridge architecture, whether it is a proposed new structure or seismical retrofitting of an existing structure, poses a great challenge to the design team. Successful bridge designs are created by the productive and imaginative creations of the bridge architect and bridge engineer working together. The partnership of these talents, although not recognized in many professional societies, is an essential union that has produced structures of notable fame, within immediate identity worldwide.

Why is this partnership considered so essential? There are a number of reasons. Initially, the bridge architect will research the existing structures in the geographic area with respect to the surrounding community's existing visual qualities of the structural elements and recommended materials, forms, and texture that will harmonize with rather than contrast with the built environment. Figure 40.17 shows the architecture success of seismic retrofit of I-5/710 Interchange in Los Angeles.

The residents of most communities that possess noted historical structures are extremely proud and possessive of their inheritance. So it is incumbent upon the bridge architect to demonstrate the sensitivity that is necessary when working on modifying historically significant bridges. This process often requires presentations at community gatherings or even workshops, where the bridge architect will use a variety of presentation techniques to show how carefully the designer has seismically retrofitted that specific structure and yet preserved the original historic design. This task is by no means easy, because of the emotional attachment a community may have toward its historic fabric.

In addition to the above-noted considerations for aesthetics, the architect and engineer must also take into consideration public safety, maintenance, and constructability issues when they consider seismic retrofit ideas. In addition to aesthetics, any modifications to an existing structure must carefully take into account the other three areas that are paramount in bridge design.

Within the governmental transportation agencies and private consulting firms lies a great deal of talent in both architecture and engineering. One key to utilizing this talent is to involve the bridge architect as early as possible so the engineer can be made aware of the important community and historical issues.

40.5 Construction

Construction is a phase of any retrofit project that is often not respected to an appropriate degree by designers. This is always somewhat of a surprise as construction regularly represents 80 to 90% of the cost of a project. In the authors opinion, a good design is driven by reliable construction methods and techniques. In order to deliver a design package that will minimize construction problems, the design project engineer strives to interact with construction engineers regularly and particularly on issues involving time, limited space, heavy lifts, and unusual specifications.

As mentioned in the section covering design, legal right-of-way access and utilities are very important issues that can stop, delay, or cause tremendous problems in construction. One of the first orders of work in the construction phase is to locate and appropriately protect or relocate utilities. This usually requires a legal agreement, which requires time. A considerable cost is not uncommon. The process required varies as a function of the utility and the owner, but they always take time and money. Access right-of-way is usually available due to existing right-of-way for maintenance. If foundation extensions or additional columns are required, then additional land may need to be acquired or even greater temporary access may be necessary. This issue should be recognized in the design phase, but regularly develops into construction challenges that require significant problem solving by the construction staff. These problems can delay a project many months or even require redesign.

Safety to the traveling public and the construction personnel is always the first priority on a construction site. But most of a structure resident engineer's (SRE) time is invested in assuring the contractors' understanding and adherence to the contract documents. In order to do this well the SRE must first understand well the contract documents, including the plans, construction standard and project special specifications. Then, the SRE must understand well the plan the contractor has to construct the project in such a way as to satisfy the requirements of the contract. It is in understanding the construction plan and observing the implementation of that plan that the SRE ensures that the construction project results in a quality product that will deliver acceptable performance for the life of the structure.

As most transportation structures are in urban areas, traffic handling and safety are important elements of any retrofit project. A transportation management plan (TMP) is a necessary item to develop and maintain. Traffic safety engineers including local highway patrol or police representatives are typically involved in developing such a plan. The TMP clearly defines how and when traffic will be routed to allow the contractor working space and time to complete the required work.

Shop plans are an item that are typically addressed early in the construction phase. Shop plans are structural plans developed by the contractor for structural elements and construction procedures that are appropriately delegated to the contractor by the owner in order to allow for as competitive bids as possible. Examples of typical shop plans include prestress anchorages and steel plate strengthening details and erection procedures.

Foundation modifications have been a major component in the bridge seismic retrofit program the California Department of Transportation has undertaken since the 1989 Loma Prieta earthquake. Considerable problems have been experienced in the reconstruction of many bridge foundations. Most of the construction claim dollars leveled against the state have been associated with foundation-related issues. These problems have included as-built plans not matching actual field conditions, materials, or dimension; a lack of adequate space to complete necessary work (e.g., insufficient overhead clearance to allow for driving or placing piles); damage to existing structural components (e.g., cutting reinforcing steel while coring); splicing of reinforcing steel with couplers or welds; paint specifications and time; and unexpected changes in geologic conditions. Although these items at first appear to have little in common, each of them is founded in uncertainty. That is, the construction problem is based on a lack of information. Recognizing this, the best way to avoid such problems is as follows:

- To invest in collecting factual and specific data that can be made available to the designer and the contractor such as actual field dimensions;
- To consider as carefully as possible likely contractor space requirements given what activities the contractor will be required to conduct;
- To know and understand well the important properties of materials and structural elements that are to be placed into the structure by the contractor; and
- To conduct appropriately thorough foundation investigation which may include field testing of potential foundation systems.

The most common structural modifications to bridge structures in California have been the placement of steel shells around portions of reinforced concrete columns in order to provide or increase confinement to the concrete within the column and increase the shear strength of the column within the dimensions of the steel shell. As part of a construction project, important items to verify in a steel shell column jacket installation are the steel material properties, the placement of the steel shell, the weld material and process, the grouting of the void between the oversized steel shell and the column, and the grinding and painting of the steel shell.

Existing reinforcing steel layouts are designed for a purpose and should not be modified. In some cases they can be modified for convenience in construction. It is important that field engineers be knowledgeable in order to reject modifications to reinforcing steel layouts that could render the existing structural section inadequate.

40.6 Costs

Estimating costs for bridge seismic retrofit projects is an essential element of any retrofit program. For a program to initiate, legislation must typically be passed. As part of the legislation package, funding sources are identified, and budgets are set. The budgets are usually established from estimates. It is ironic that, typically, the word *estimate* is usually dropped in this process. Regardless of any newly assigned title of the estimate, it remains what it is — an estimate. This typical set of circumstances creates an environment in which it is essential that great care be exercised before estimates are forwarded.

The above being stated, methods have been developed to forecast retrofit costs. The most common technique is to calculate and document into a database project costs per unit deck area. When such data are nearly interpolated to similar projects with consistent parameters, this technique can realize success. This technique is better suited to program estimates rather than a specific project estimate.

TABLE 40.2 Approximate Costs of Various Pay Items of Bridge Seismic Retrofit (California, 1998)

Pay times	Approximate Cost	Notes
Access opening (deck)	\$350 to \$1500 per sq. ft.	
Access opening (soffit)	\$400 to \$750 per sq. ft.	
Restrainer cables	\$3.5 to \$6.6 per number	
Restrainer rods	\$2.5 to \$4.5 per number	
Seat extenders	\$1.5 to \$3.3 per number	
Steel shells for columns	\$1.5 to \$2.25 per lb.	
Concrete removal		
Steel removal		
Soil removal	\$40 to \$150 per cy	
Core concrete (6 in.)	\$65 to \$100 per ft.	
Concrete (bridge footing)	\$175 to \$420 per cy	
Concrete (bridge)	\$400 to \$800 per cy	
Minor concrete	\$350 to \$900 per cy	
Structural steel	\$2.50 to \$5 per lb.	
Prestressing steel	\$0.80 to \$1.15 per lb.	
Bar reinforcing steel	\$0.50 to \$1.00 per number	
Precast concrete pile (45T)	\$610 to \$1515 per linear ft.	
CISS piles (24 in.)	\$788 to \$4764 per linear ft.	
Pile shaft (48 in.)	\$170 to \$330 per linear ft.	
Structural backfill	\$38 to \$100 per cy	
Traffic lane closure (day)		
Traffic lane closure (night)		

When applied to a specific project, additional contingencies are appropriate. When an estimate for a specific project is desired, it is appropriate to evaluate the specific project parameters.

Many of the components or pay items of a seismic retrofit project when broken down to pay items are similar to new construction or widening project pay items. As a first estimate, this can be used to approximate the cost of the work crudely. Table 40.2 lists the approximate cost for various pay items in California in 1998. There certainly are exceptions to these general conditions, such as steel shells, very long coring and drilling, and pile installation in low clearance conditions.

40.7 Summary

The two most significant earthquakes in recent history that produced the best information for bridge designers were the 1989 Loma Prieta and the 1994 Northridge events. Although experts consider these to be only moderate earthquakes, it is important to note the good performance of the many bridges that had been designed for the improved seismic criteria or retrofitted with the early-era seismic retrofit details. This reasonable performance of properly designed newer and retrofitted older bridges in a moderate earthquake is significant for the rest of the United States and other countries because that knowledge can assist engineers in designing new bridges and in designing an appropriate seismic retrofit program for their older structures. Although there is a necessary concern for the “Big One” in California, especially for the performance of important structures, it must be noted that many structures that vehicle traffic can bypass need not be designed or retrofitted to the highest standards. It is also important to note that there will be many moderate earthquakes that will not produce the damage associated with a maximum event. These are the earthquake levels that should be addressed first in a multiphased retrofit strengthening program, given the limited resources that are available.

Cost–benefit analysis of retrofit details is essential to measure and ensure the effectiveness of a program. It has been the California experience that a great deal of insurance against collapse can be achieved for a reasonable cost, typically 10% of replacement cost for normal highway bridges. It is also obvious that designing for the performance criteria that provides full service immediately after a major earthquake may not be economically feasible. The expected condition of the bridge approach roadways after a major seismic event must be evaluated before large investments are made in seismic retrofitting of the bridges to the full-service criteria. There is little value to the infrastructure in investing large sums to retrofit a bridge if the approaches are not functioning after a seismic event. Roadways in the soft muds around most harbors and rivers are potentially liquefiable and will require repair before the bridges can be used.

Emerging practices on bridge seismic retrofit in the state of California was briefly presented. The excellent performance of bridges utilizing Caltrans newer design criteria and ductile details gives bridge designers an indication that these structures can withstand a larger earthquake without collapse. Damage should be expected, but it can be repaired in many cases while traffic continues to use the bridges.

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