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# US PERSPECTIVES ON SEISMIC DESIGN OF BRIDGES

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## ABSTRACT

Six years have passed since the disastrous Loma Prieta earthquake and over five years have passed since the Governor's Board of Inquiry into the cause of highway structure failures during that earthquake issued its final report with the warning title "Competing Against Time". It is the purpose of this paper to discuss the Seismic Design Specifications and Construction Details that have been developed in California as lessons were learned from the 1971 San Fernando earthquake and subsequent seismic events; and to discuss the unprecedented research program that has provided the bridge design community the assurance that the new specifications and details perform reliably. 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 Board of Inquiry report. The six year old Seismic Advisory Board has been an invaluable asset in reviewing the performance criteria, design specifications, and design procedures for both new design and retrofit strengthening of older, non-ductile bridges. In many instances the Advisory Board has positively influenced management decisions to continue financial support of a strong research program to support seismic design and retrofit, through its recommendations to the Director of Transportation.

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 program has been supported at a level more than ten times the pre Loma Prieta level of financial support for all bridge research. The Department has been able to sustain the necessary high level of research support over the past six years, and has adopted a commitment for that level of funding for the forseeable future.

Until recent years most other states in the United States have not been concerned with seismic design for bridges. However, some 37 states in the US have some level of seismic hazard. The American Association of State Highway and Transportation Officials (AASHTO) is the agency responsible for development of bridge design specifications for nationwide use. AASHTO has typically adopted seismic design criteria modeled after those developed in California. Understandably, there are hundreds of bridges in these other states which have been designed to seismic criteria that are not adequate for seismic forces and displacements that we know today. The seismic retrofit details designed by the California bridge engineers can be of great benefit to those states who are faced with seismic threats of lesser magnitude, and with little financial support for seismic retrofitting, and much less for research and seismic detail development.

## KEY WORDS

Seismic Retrofit, Hazard Analysis, Vulnerability Assessment, Ductility, Displacements, Soil-Structure Interaction, Confinement, Non-linear Analysis

# INTRODUCTION

Prior to the 1933 Long Beach earthquake there was no special consideration for seismic design of buildings or bridges in California. The severe damage to schools that resulted from that seismic event resulted in creation of the Structural Engineer license and a requirement for special consideration of seismic forces in the design of public schools in California. After the 1940 El Centro earthquake the bridge design office of the California Division of Highways developed minimal seismic design factors for bridges. The 1940 El Centro record was digitized and used as the seismic design spectra for over 30 years before an earthquake of greater magnitude occured in California. The 1971 San Fernando earthquake caused severe damage to hospitals, public utilities, and freeway bridges, recording a peak ground acceleration of 1.0g and large ground displacements. This earthquake caused both building and bridge designers to revise their design criteria and structural details to provide better resistance to the forces and displacements of major seismic events. The American Association of State Highway and Transportation Officials (AASHTO) is the agency responsible for development of bridge design specifications for nationwide use. AASHTO has typically adopted seismic design criteria modeled after those developed in California, and the initial adoption is only as a guide specification. Until recent years most other states in the United States have not been concerned with seismic design for bridges, considering it a California or West Coast problem. For example, the 1940 California seismic design specifications were not adopted by AASHTO until 1961, and the 1973 California seismic design specifications were not adopted nationally until 1983. In May, 1990, responding to the disastrous 1989 Loma Prieta earthquake in California, AASHTO finally adopted the 1983 "Guide Specifications For Seismic Design of Highway Bridges" as a mandatory requirement for those states which have a seismic hazard. Interestingly, some 37 states in the US have some level of seismic hazard. Understandably, there are hundreds of bridges in these other states which have been designed to seismic criteria that are not adequate for seismic forces and displacements that we know today. The seismic retrofit details designed by the California bridge engineers can be of great benefit to those states who are faced with seismic threats of lesser magnitude, and with little financial support for seismic retrofitting, and much less for research and seismic detail development.

The California State Department of Transportation (Caltrans) owns and maintains over 12,000 bridges (spans over 20 feet). There are an equal number on the City and County system. The bridge office maintains the condition data for all these and some 6,000 other highway structures such as culverts (spans under 20 feet), pumping plants, tunnels, tubes, Highway Patrol inspection facilities, maintenance stations, toll plazas and other transportation related structures. Structural details and the current condition data are maintained in the department's bridge maintenance files as part of the National Bridge Inventory System (NBIS) required by the US Congress and administered by the Federal Highway Administration (FHWA). This data is updated and submitted annually to the FHWA and is the basis upon which some of the Federal gas tax funds are allocated and returned to the states. The maintenance, rehabilitation and replacement needs for bridges are prorated against the total national needs.

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. While the 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 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 which 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 multi phased retrofit strengthening program, given the limited resources that are available. Cost benefit analysis of retrofit details is essential to measure and insure 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 ten percent of replacement cost. It is also obvious that designing for a 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 the bridges to a 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.

Approximately 2,200 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 1,200 of these bridges were in an area that experienced ground accelerations greater than 0.25g and several hundred were in the area that experienced ground accelerations of 0.50g or greater. There were 132 bridges in this area with post San Fernando retrofit details completed and 63 with post Loma Prieta retrofit details completed. All of these retrofitted bridges performed extremely well and most of the other bridges performed well during the earthquake; newer bridges designed and constructed to Caltrans' current seismic specifications survived the earthquake with very little damage. Seven older bridges, designed for a smaller earthquake force or without the ductility of caltrans' current 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.

## SEISMIC DESIGN PHILOSOPHY

Performance Criteria-An agency or designer must have a seismic performance criteria established. How do you want the structure to perform in an earthquake? How much damage can you accept? What are the reasonable alternate routes? A bridge seismic performance criteria was developed by Caltrans' Engineering staff for state owned bridges and was approved by the Seismic Advisory Board in September, 1992. That current Performance Criteria is **"No Collapse", "No Major Damage", "No Secondary Injuries or Fatalities Because Emergency Equipment Cannot Get Through", "Major Important Structures and Lifeline Routes Must Remain Operational".** This criteria is generally attainable but the last one can be expensive if structures are expected to withstand severe earthquakes such as a 45 second duration shake due to large earthquakes on a major fault. That is what is expected of major important structures in California and the 45 second duration shake is what the experts predict when the "Big One" comes.

Seismic Design Principles-**Continuity** is extremely important and is the easiest and cheapest insurance to obtain. 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 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.

Nonlinear Analysis Procedures-Prior to the Loma Prieta event there was little use of nonlinear analysis in the design of bridges. In order to correctly analyze bridge performance in a major earthquake of long duration, the use of nonlinear analysis techniques is mandatory. Ample research has been completed in this area to give designers the necessary tools to conduct reasonable nonlinear analyses and design structures that will perform in a ductile manner during a major earthquake with long duration. Additional work in this area will continue to improve the expertise of and build confidence in the bridge designers.

Steel versus Concrete-While it can be argued that steel is inherently more ductile than concrete, it must also be remembered that the materials must be designed to resist the current anticipated seismic forces. Most damage in California during the Loma Prieta earthquake occured on structures that had been designed 30 to 60 years ago to comply with codes that required seismic design forces of only 0.06g to 0.08 g. Today most of those structures would be designed for 8 to 10 times these seismic forces. The forces are derived from the acceleration coefficients multiplied by the weight of the contributing mass at any supporting member or joint. A quick survey of most bridges in this country will confirm that almost all have reinforced concrete substructures, regardless of the type of superstructure. And the substructures are where most of the earthquake damage occurs. Since we rely on internal strain energy to dissipate the external work (energy), concrete substructure elements are preferrable, as long as they are properly confined and will remain intact. Internal damage can be repaired after a seismic event.

Seismic Design Research Program-The Governor's Board of Inquiry recommended that Caltrans "Fund a continuing program of basic and problem-focused research on earthquake engineering issues pertinent to Caltrans responsibilities." The initial Legislative investment in bridge seismic research was $8 million. Subsequently, the Department management has agreed to a problem-focused seismic research program at an

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annual expenditure level of $5 million (approximately 1% of the Caltrans annual bridge capital expenditure program). It is this last recommendation that gave impetus to the major seismic research work which is being supported by the Department today and through which we are supporting the annual seismic research workshops. The workshops serve a major goal of technology transfer to the user community. All bridge seismic details for new design and retrofit have been proof tested in the university laboratories before being implemented in the final structures.

## SEISMIC DESIGN SPECIFICATIONS AND PROCEDURES FOR BRIDGES

A major element of the improved seismic design specifications and procedures was the adoption of a site specific seismic design philosophy shortly after the 1971 San Fernando earthquake. The California Division of Mines and Geology (CDMG) was engaged for the development of an earthquake ground fault map. The maximum credible events on seismic faults throughout the state define peak bedrock acceleration levels. The current version is CDMG Map Sheet 45. This document maps the 275 known faults and includes contours of various levels of expected peak rock acceleration determined from average attenuation relationships developed by various seismologists. This approach has been criticized as too conservative but our cost analyses show that the additional cost for an average bridge is less than one percent for the maximum credible event versus design for a probabilistically determined event. Considering the limited ability to determine a probabilistic earthquake with a high degree of confidence and the high cost for a site specific study, we feel that the maximum credible approach for the smaller bridges is the most reasonable approach, given the current state of seismological event predictions. Since the 1989 Loma Prieta earthquake Caltrans has utilized a site specific hazard analysis to determine the most probable design earthquake for major structures. This event is incorporated into the seismic design procedure along with the maximum credible event.

In 1973 Caltrans, working with Professor Harry Bolton Seed at UC Berkeley, then developed a series of Acceleration Response Spectra (ARS) for alluvium and harder soils of various depths above bedrock. These spectra have been used for determining the appropriate seismic design force for typical freeway bridges in California. After the 1989 Loma Prieta earthquake the staff and consultants began developing a similar set of response spectra for deep, soft soils. It is apparent, however, that more site specific soil studies must be used for bridges being built or retrofitted over softer soil foundations.

## COLUMN DESIGN AND RETROFIT

While the hinge and joint restrainers performed well, shear failure of columns on the I-605/I-5 separation bridge in Los Angeles during the moderate Whittier Earthquake of October 1, 1987 reemphasized the inadequacies of pre-1971 column designs. Even though there was no collapse, the extensive damage resulted in plans for basic research into practical methods of retrofitting bridge columns on the existing pre-1971 non-ductile bridges. That research program had already been initiated in early 1987 at the University of California at San Diego and the Whittier earthquake merely speeded its approval and execution. The continuing bridge seismic retrofit research is currently being conducted at the University of California at San Diego, the University of California at Berkeley, and other University and private research facilities. Funding levels for seismic retrofit program implementation were increased four fold after the Whittier earthquake to an annual program of $16 million. Even at that level it would have required some 100 years to complete the retrofitting program that was identified.

Most 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 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 (3/4 inch diam.) hoops or continuous spiral at approximately three inch pitch over the full column height. This reinforcement detail provides approximately eight times the confinement and shear reinforcing steel in columns than what was used in the pre-1971 non-ductile 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.

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 immediately accelerate the column retrofit phase of the bridge seismic retrofit program with a higher funding level for both research and implementation. Other structures in the earthquake affected counties performed well, suffering the expected column damage without collapse. With the exception of a single outrigger column-cap joint confinement detail, those bridges using the post 1971 design specifications and confinement details performed well. Damage to long, multiple level bridges showed the need to more carefully consider longitudinal resisting systems because earthquake forces cannot be carried into abutments and approach embankments as they can on shorter bridges. After the Loma Prieta earthquake caused 44 fatalities on the State Highway System, capital funding for bridge seismic retrofitting was increased to $300 million per year. At the same time bridge seismic research funding was increased from $0.5 million annually to $5.0 million annually with an initial $8.0 million allocation from the special State Emergency Earthquake Recovery legislation of November, 1989 (Senate Bill 36X).

The greatest number of large scale tests have been conducted to confirm the calculated ductile performance of older, non-ductile bridge columns that have been strengthened by application of structural steel plate, prestressed strand or epoxy- fiberglass composite jackets to provide the confinement necessary to insure ductile performance. Since the Spring of 1987 the researchers at UC San Diego have completed more than 50 sets of tests on bridge column models. Priestley, Seible and others at UC San Diego have published numerous research reports on this work.

## RESPONSE OF DEEP SOFT SOILS

The Acceleration Response Spectra (ARS) developed after the 1971 San Fernando earthquake were developed for harder soils and alluvium but were not accurate for prediction of the dynamic response of softer soils and bay muds. After the Loma Prieta earthquake Caltrans immediately engaged Professors John Lysmer and Raymond B. Seed at UC Berkeley to help develop a set of similar ARS curves for deep, soft soils and mud. Professors Lysmer & Seed and C.M. Mok & S.E. Dickenson of UC Berkeley have concluded that the deep, soft muds amplify the bedrock ground motions by factors of 2 to 3 and that amplification of the longer period components is especially pronounced, resulting in surface motions that are more damaging to the taller, longer period structures. Seismic ground motions have been predicted in the deep, soft soils with an analytical procedure and those predictions have been confirmed with the actual recorded Loma Prieta motions at four sites around the San Francisco Bay. The Applied Technology Council project ATC-32 has provided a series of ARS curves for various soft soil conditions to augment those already in use.

Other geotechnical factors that contributed to structural damage in the Loma Prieta earthquake were non-uniform and out of phase response of the foundation materials and their affect on longer structures such as the 1.5 mile long viaducts and the San Francisco-Oakland Bay Bridge. The effect of non-coherent soil response is now being considered in the site specific response spectra that are developed for longer structures. While soil liquifaction was not a contributor to bridge damage, it was apparent near several major structures in the East Bay and must be considered and dealt with in future seismic design for bridges. Results of studies by Lysmer, Seed, Idriss and other investigators clearly indicate the shortcomings of the current provisions for dealing with the influence of deep, soft foundations on structure response. In addition to developing the new set of ARS curves for deep, soft soils, Caltrans has also initiated a program to identify and map the soft soil sites in the state. Caltrans intends to develop a set of generic ARS curves for several representative deep, soft soil site conditions for use on the more standard and smaller bridges but, upon the recommendation of Doctor Seed and other advisors, we will concentrate on site specific response analyses for all structures at soft soil sites. These researchers have shown that the analysis techniques and the computer programs currently available can reliably predict the response of deep, soft soils, and therefore, justify site specific analyses. For the major Bridges crossing the Bays from San Diego in the South to Antioch at the extreme Northeast end of the San Francisco Bay we have engaged consultants to conduct site specific complete hazard analyses using a probabilistic approach to provide the design earthquake for bridge seismic design purposes.

Working with in-house Engineering Geologists & Geotechnical Engineers and several Consultants, Caltrans is also indentifying and mapping the sites which could potentially liquify and working with Professor Geoffrey Martin at the University of Southern California and others to develop design mitigation procedures for those sites. For one site north of San Diego at Del Mar Heights, adjacent to the Pacific

Ocean, Caltrans is using 16 inch diameter stone columns to stiffen the soil around the bridge piers. For the major Mission Valley interchange between Interstate Routes 8 and 805 in San Diego extensive substructure modifications are being incorporated to overcome the foundation strength loss due to liquefaction in a major seismic event. Jackura and Abghari of Caltrans have reported on the Mitigation of Liquefaction Hazards at Three California Bridge Sites, including the two in San Diego.

## SEISMIC DESIGN PROCEDURES FOR BRIDGE STRUCTURE/ FOUNDATION INTERACTION

The two major considerations in seismic design of foundations are ground motion and foundation & substructure interaction. Caltrans adopted a site specific seismic design philosophy shortly after the 1971 San Fernando earthquake. The maximum credible events on seismic faults throughout the state define peak bedrock acceleration levels as shown on the California Division of Mines and Geology Map sheet 45. For the average smaller freeway structures we use the Maximum Credible Earthquake (MCE) for determining the seismic design forces. For major structures we use a site specific probabilistic hazard analysis to determine the most probable design earthquake spectra. These spectra are incorporated it the seismic design analysis along with the maximum credible event. This approach provides a good check of the two procedures and assures the use of the worst case seismic coefficients for lateral force design.

By 1973 Caltrans had developed a series of Acceleration Response Spectra for various depths of alluvium over the bedrock. These spectra have been used for determining the appropriate seismic design lateral force for typical freeway bridges in California. As discussed previously, we are currently in the process of developing a similar set of spectra for deep, soft soils. It is apparent, however, that more site specific studies must be used for bridges being built or retrofitted over softer soil foundations. For example, five significantly different soil conditions, ranging from deep, soft bay mud (over 100 feet thick) to bedrock at the surface exist along the length of the Terminal Separation Structure at the west end of the San Francisco-Oakland Bay Bridge, and five different foundation acceleration response spectra have been developed for the structural dynamic response analysis of variuos frames in this structure.

The design procedure involves modeling of the structure and foundation, including the foundation material stiffness and pile/footing stiffness using appropriate soil springs. Using this model and the appropriate design earthquake record a dynamic analysis is conducted to initially size the column dimensions and reinforcing steel patterns. The columns are sized to provide moment and shear ductility capacity greater than the joint ductility demands generated by the analysis program. This procedure is iterative, requiring several cycles to converge on the correct column sizes. After the initial column sizing the foundations are designed to resist the plastic moment ($M_p$) and plastic shear ($V_p$) capacity at the base of the column, determined by the properties of the column concrete section and the reinforcing steel pattern. An allowable overstrength of 30% is typically applied to the column moments and shears for foundation design, to account for the ductile performance of the column in a seismic event. From this point forward the foundations are designed without additional seismic input.

Caltrans had also developed a series of reduction factors for reducing the seismic design force based on the ductility inherent in the structural framing of the bridge, the degree of acceptable risk we were willing to take, and the amount of structural damage we would accept. These factors have been developed empirically, based on actual damage patterns recorded in California earthquakes since 1971. Seismic lateral forces are reduced using these factors but the joint displacements are not reduced from those actually calculated from the dynamic analysis. It is important to note that the reduction factors for shear keys and hinge restrainers are 0.90 and 1.00, respectively. These factors actually result in conservative design for these details but it is felt that the relatively low cost of these elements and the difficulty of inspecting them after an event warrants the conservative design. This philosophy has been proven to be correct, based on damage to interior hinge details in the 1994 Northridge earthquake. Since the Loma Prieta event we have retained the Applied Technology Council (ATC) to review our seismic design criteria and recommend appropriate changes, if necessary. The project, now underway as ATC-32, was completed in August, 1995 and the final report is due in early 1996, but interim results have been implemented already. The Ductility and Risk Reduction Factors is one of the major elements of the current criteria that require some adjustment and it was studied as a first order of work in the ATC project. Some experts feel that the current factors are not conservative enough in the short period range and too conservative in the long period range. The AASHTO Seismic Bridge Design Specifications which are used by other states utilize similar factors designated as "R" factors, which are generally more conservative than those used by California. It is anticipated that Caltrans will have new Risk and Ductility factors by the summer of 1996, and they will undoubtedly be more conservative than the current factors.

The proper modeling of bridge foundations is essential to achieving an accurate dynamic response of the foundations and their influence on the structural response of the bridge. Doctor I. M. Idriss has developed a procedure for predicting the ground response at soft soil sites using the computer program SHAKE and currently available ground and bedrock seismic response records. He has achieved reasonable agreement between recorded and calculated motions, so it is now possible to predict the ground motion characteristics of soft soil sites with a reasonable degree of confidence.

Doctors Po Lam, Roy Imbsen and Geoffrey Martin have discussed modeling of bridge foundations in a paper which was given at the Third Transportation Research Board (TRB) Bridge Engineering Conference at Denver, Colorado on March 10, 1991. Dr. Po Lam has found in his studies that the Caltrans recommendations to designers for abutment soil response given in Bridge Design Aids, Section 14 compare favorably with response characteristics calculated using Wilsons equation. With the techniques described in these papers and the work of other researchers it is not difficult to properly model the bridge structural elements and the bridge foundations.

The major factors to be considered in modeling bridge abutments are the stiffness of abutment systems, the soil pressure on abutment end walls and wingwalls, and the interaction between abutment inertia forces from the deck system versus the induced soil pressure. The UC Davis research project, headed by Doctor Karl Romstad deals with bridge abutment load/displacement characteristics. The work was conducted by Caltrans engineer Dr. Brian Maroney as part of his Doctoral Dissertation. This work will add to the limited data now available.

Lam, Imbsen and Martin recommend an Iterative Design Procedure for abutment design using the four steps below. Caltrans has been using this procedure since the Loma Prieta earthquake, and similar procedures since 1973.

(1) Assume abutment stiffnesses based on abutment parameters and standard soil properties.

(2) Conduct a Dynamic Response Analysis using the assumed abutment stiffnesses.

(3) Check soil pressure versus soil capacity; if pressure exceeds capacity, repeat the analysis with reduced abutment stiffnesses. Repeat iterations until convergence is achieved.

(4) Check abutment displacement and compare with original assumptions. Repeat analysis with revised stiffness if necessary to achieve a realistic displacement.

Footing design is handled in much the same manner, based on lateral load test data to determine lateral resistance of pile footings and pile groups as well as spread footings. Actual values can be used or appropriate soil spring constants can be used in modeling to conduct a dynamic response analysis of the structure. The lateral load tests reported by Abcarius and discussed at length by Lam provide valuable data for a limited number of pile load tests. More lateral load tests must be conducted to increase the reliability of predictions. For many soft sites, site specific lateral load tests must be conducted until the bridge engineering profession has developed sufficient knowledge in this area to develop good soil/structure interaction data and soil spring constants. Imbsen, Lam and Martin discuss the proper procedures for substructure design in their work for input to the FHWA course on Seismic Design of Highway Bridges.

For many bridge supports the use of single column bents is popular in California and it is necessary to develop uplift capacity in the foundation piling due to overturning moments. James Mason of Caltrans conducted a series of pile tests for various proprietary piles and micro-piles in the deep mud site below Interstate Highway 280 in South San Francisco. Design loads for these Micro Piles are now available and can be specified by the designers. Load tests to confirm required length at each deep soft soil site are still required, but these proprietary systems are pre-approved for use.

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# DUCTILE DESIGN DETAILS

Caltrans has used ductile design philosophy since developing the current seismic design specifications in 1973. It is considered too expensive to design all bridge components for earthquake loading to remain within the elastic range. An acceptable approach in the design of earthquake resistant structures is to allow some local and controlled yielding. In bridge structures this commonly takes the form of designed fuses at the base or top of columns as potential plastic hinges. Effective fusing at the footing greatly reduces the moments and shears that transfer into the footings and makes footing analysis easier. Also, the ductility prevents the development of brittle failures. This is especially helpful in retrofitting older existing bridges.

Beam-Column Joint Confinement-Major advances have also been made in the area of beam-column joint confinement, based on the results of research at both UC Berkeley and UC 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 was reported by Cooper of Caltrans. Research is continuing at both Institutions to further refine the design details to ensure ductile performance of these joints. Large one-half scale models of the most critical three-way longitudinal edge beam, transverse bent cap, column joint detail were built and tested at both UC San Diego and UC Berkeley as a major element of the joint and column testing program. Additional large scale model testing programs are planned for the more complex multi-level beam-column details commonly used in major highway interchange structures. Mahin and Moehle of UC Berkeley, and Seible of UC San Diego have published reports of their research in this area.

Edge Beam-Column-Bent Cap joint detail-The most elaborate and expensive tests conducted to date have been the half scale and third scale models of the proposed retrofit details for the double deck viaduct structures in San Francisco. Models, using two different seismic retrofit techniques, were tested at both UC San Diego (Half scale) and UC Berkeley (Third Scale) in order to obtain the performance characteristics of the two different details so Caltrans' designers and consultants could make the final design and construction decisions and get the construction contracts started in 1992. Both models were nearly 50 feet long by 20 feet wide and 20 feet high. They included one-half of each span adjacent to the joint and half the column above and below the joint. Half width of the superstructure was also modeled to recreate the actual contributing dead load and stiffness of the elements that frame into these columns. The difference in the concepts is in the connection to edge of deck of the original structure. The UC Berkeley concept uses an integral edge beam detail which is necessary on curved alignments, such as the Central Viaduct (US 101) in Downtown San Francisco and the Alemany Interchange on US 101 in South San Francisco. This research and testing program was reported by Mahin.

The UC San Diego concept is an independent edge beam which will be used on straight alignments, primarily the I-280 Southern Freeway Viaduct north of the Alemany Interchange with US 101. This research was reported by Priestley. Thirteen dynamic actuators were required to dynamically excite the UC San Diego model in all three directions. The beginning of plastic hinge formation at the top of the lower column occured at design ductilities, exactly where the design intended to force its location. After a ductility of 8 had been achieved, the plastic hinge zone began to lose its cover but the core concrete remained intact because of the heavy confinement reinforcement and therefore the structure should remain standing and in operational service. This level of damage is easily repaired after a seismic event without closure to public traffic. Each of these test series represents a cost of $500,000 but they are used to proof test the intended retrofitting scheme for structures totalling more than one mile in length with a replacement cost of over $200 million. Mahin and Moehle of UC Berkeley and Priestley and Seible of UC San Diego have published results of their work.