the UC Berkeley - CUREE Symposium in Honor of Ray Clough and Joseph Penzien
Berkeley, California
May 9-11, 2002

Joseph Penzien

Ray Clough

1948, "A Simplified Polarscope for Industrial Use"
1949, "Applying the Polarscope to Structures Under Long Duration Impulsive Loads"
1950, "Structural Analysis of a Three-Story Frame Subjected to Earthquake Loading"
1951, "Influence of Higher Modes of Vibration in the Earthquake Response of Tall Buildings"
1952, "Dynamic Effects of Earthquakes"
1953, "Dynamic Effects of Earthquakes"
1954, "Effect of Earthquake on Structures"
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2001, "Effect of Earthquake on Structures"
2002, "Effect of Earthquake on Structures"
Preface

The Proceedings of the UC Berkeley – CUREE Symposium in Honor of Ray Clough and Joseph Penzien is a volume that collects abstracts of presentations made at the Symposium honoring two of the most influential researchers and educators in structural and earthquake engineering. In addition to appropriately honoring Professors Clough and Penzien for their major contributions to the engineering field, the Symposium and this document serve a second important purpose: to provide the current generation of academic and practicing engineers with insights concerning the origins of some of the key knowledge and techniques they depend on today. Because the concepts and engineering methods pioneered by Dr. Clough and Dr. Penzien have been so extensively verified and adopted into practice, and because their breakthroughs now constitute material that is so routinely included in textbooks, it is all too easy to take for granted their historic contributions.

The same pair of purposes—to give honor where honor is due, and to document some major developments in civil engineering aspects of earthquakes over the past few decades of rapid advancement—has formed the basis for the previous symposia in this series, which are listed below. In each case, the co-sponsorship indicates the high regard shown toward the individual by both their home institution (in the present case, the University of California at Berkeley) and by their peers throughout academe (facilitated through the Consortium of Universities for Research in Earthquake Engineering).

• George Housner, California Institute of Technology, 1995\(^{(1)}\)
• Vitelmo V. Bertero, University of California at Berkeley, 1997\(^{(2)}\)
• Haresh C. Shah, Stanford University, 1997\(^{(3)}\)
• Takuji Kobori, University of Kyoto, 2000\(^{(4)}\)

The financial support of several organizations for the Clough-Penzien Symposium is gratefully acknowledged. The National Science Foundation (program managers Dr. Peter Chang and Dr. S. C. Liu) provided a grant to the University of California at Berkeley to facilitate the attendance at the Symposium of graduate students and younger faculty from around the United States. Funding to support the Symposium was also provided by the Earthquake Engineering Research Institute, Mid-America Earthquake Center and Pacific Earthquake Engineering Research Center. On the occasion of the Symposium, a Clough-Penzien Fund has been established at the University of California, Berkeley, to support the program in Structural Engineering, Mechanics and Materials, as described in the introductory pages of these Proceedings (page v). Contributions to this Fund are acknowledged separately.

Through their students, their professional engineering colleagues, and the legacy of their advancements in engineering methods and concepts, Dr. Clough and Dr. Penzien continue to exert a significant influence on engineering today. This influence extends across many sub-disciplines and many countries as discussed in these Proceedings. The session chairs and presenters, who represent the many branches of that influence, form the heart of the Symposium’s program, and their enthusiastic willingness to participate in it has been essential to its success. We gratefully acknowledge their contributions. The dual purposes of the Symposium—to honor Professors Clough and Penzien, and to provide an instructive experience for the attendees of the event and the readers of this document—are reflected in the dual way the presenters have woven past and future into their presentations: Personal accounts of contacts with Ray Clough and Joseph Penzien, which in many cases extend back several decades into the twentieth century, are juxtaposed with thoughts concerning further developments we can look forward to in the twenty-first century.
Arrangements for the Symposium were capably handled by Reed Helgens, CUREE’s Information Coordinator, who smoothly dealt with the many planning, budgetary, and logistical exigencies that inevitably arise in putting on such an event. She was assisted by Leah Radke of CUREE and by Gloria Partee of the UC Berkeley Structural Engineering, Mechanics and Materials Program. John-Michael Wong of CUREE provided information technology assistance. Darryl Wong, Website and Publications Coordinator of CUREE, compiled and graphically designed these Proceedings. We are grateful for their invaluable assistance.

Organizing Committee of the UC Berkeley-CUREE
Symposium in Honor of Ray Clough and Joseph Penzien

Armen Der Kiureghian, Chair, University of California at Berkeley
Anil Chopra, University of California at Berkeley
Helmut Krawinkler, Stanford University
Jack Moehle, University of California at Berkeley
Robert Reitherman, Consortium of Universities for Research in Earthquake Engineering
Wen Tseng, International Civil Engineering Consultants, Inc.
Edward Wilson, University of California at Berkeley

Notes

(1) The CUREe Symposium in Honor of George Housner, co-sponsored by the California Institute of Technology and California Universities for Research in Earthquake Engineering (or CUREe, which is now CUREE—Consortium of Universities for Research in Earthquake Engineering), held October 27 and 28, 1995 at the Doubletree Hotel in Pasadena, California; Richmond, CA: CUREE, 1995.

(2) The EERC-CUREe Symposium in Honor of Vitelmo V. Bertero, co-sponsored by the Earthquake Engineering Research Center (EERC) of the University of California at Berkeley and CUREe; held January 31 and February 1, 1997 at the Berkeley Marina Marriott Hotel; UCB/EERC-97/05; Richmond, CA: EERC, 1997.

(3) Symposium and Banquet to Honor Professor Haresh C. Shah: Risk Management and Mitigation for Natural Hazards, Department of Civil Engineering, Stanford University; co-sponsored by Stanford University and CUREe; held April 25-26, 1997 at Stanford University; Palo, Alto, CA: Stanford University Department of Civil Engineering, 1997.

(4) Earthquake Engineering in the Next Millennium: Symposium in Honor of Takagi Kobori, co-sponsored by the Kobori Symposium Japan Committee and CUREe; held November 7, 2000 in Nara, Japan; Kyoto, Japan: International Institute for Advanced Studies, 2000.
Clough-Penzien Fund
In support of UCB-CEE Program in Structural Engineering, Mechanics and Materials

On the occasion of this Symposium, the University of California has established the Clough-Penzien Fund in support of the Structural Engineering, Mechanics and Materials (SEMM) Program within the Department of Civil and Environmental Engineering. The Clough-Penzien Fund will be used to enrich the education of students in structural and earthquake engineering at UC Berkeley by sponsoring seminars, supporting student organization activities, inviting visitors of national prominence to meet and work with students, and upgrading student office space. The Fund will also be used for outreach and recruiting of future generations of students interested in structural engineering careers. The Fund will help maintain the quality of structural and earthquake engineering programs that Professors Clough and Penzien helped raise to world prominence.

Tax-deductible contributions to the Clough-Penzien Fund can be made by sending a check to the Chair of SEMM, 721 Davis Hall, MC 1710, University of California, Berkeley, CA 94720-1710. Make the check payable to “The Regents of UC” with a note that it is intended for the “Clough-Penzien Fund in SEMM.”
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THURSDAY - MAY 9, 2002

RECEPTION

5:00-7:00 PM  Hors d’oeuvres / Hosted Bar
UC Berkeley Faculty Club

FRIDAY - MAY 10, 2002
All sessions will be held in Sibley Auditorium in the Bechtel Engineering Center

TECHNICAL SESSIONS

8:00-8:30 AM  Continental Breakfast
Garbarini Lounge (outside Sibley Auditorium)

8:30-8:45 AM  Opening Session
A. Der Kiureghian, Chair, Organizing Committee
R. Newton, Dean, College of Engineering, University of California at Berkeley
A. Kanafani, Chair, Department of Civil and Environmental Engineering
A.Filiatrault, President, Consortium of Universities for Research in Earthquake Engineering (CUREE)

8:45-10:15 AM  Session 1 - Dynamics of Structures
A. Chopra (Session Chair), Ray Clough and Joseph Penzien: My Mentors
J. Roesset, Dynamic Analyses in the Frequency Domain
P. Fajfar, Relations Between Quantities Controlling Seismic Response
W-S Tseng, Dynamics of Structures in Earthquake Engineering of Bridges
P. Gulkan, A Simple Approximation for the Drift Spectrum

10:15-10:40 AM  Break

10:40-12:30 PM  Session 2 - Finite Element Method
E. Wilson (Session Co-Chair), A Small Subset of Finite Element Students
K. Gerstle (Session Co-Chair), The Finite-Element Method - A Little History
Y. Rashid, Computational Veracity of the Finite Element Method in Concrete Structural Analysis
C. A. Felippa, History of Matrix Structural Analysis, Act III: The Boeing-Berkeley Connection
P. Bergan, Finite Elements - Free Style
K. Willam, From Finite Elements to the Berkeley Connection
K.-J. Bathe, Key Challenges at 40 Years After

12:30-2:00 PM  Lunch
Served on the Bechtel Plaza, outside, adjacent to Sibley Auditorium
TECHNICAL SESSIONS

2:00-3:30 PM  Session 3 - Strong Motion Seismology
P. C. Jennings (Session Chair), Strong Motion Seismology - An Introduction
C. S. Oliveira, (No title available)
C.-H. Loh, Hazard-Consistent Description of Seismic Force for Taiwan Seismic Codes
R. D. Borchert, Viscoelastic Wave Propagation in Layered Soil Deposits: A Tale of Theory from EERC to the IBC
N. Abrahamson, Velocity Pulses in Near Fault Ground Motions

3:30-4:00 PM  Break

4:00-5:10 PM  Session 4 - Probabilistic Methods
C. C. Tung (Session Chair), A Statistical Model for a Certain Construction Model
A. H.-S. Ang, Probabilistic Methods in Seismic Hazard Analysis and Optimal Seismic Design of Structures
L. Esteva, Probabilistic Models of Seismic Response and Performance for Engineering Design Practice
A. Der Kiureghian, Deterministic Recollections, Probabilistic Finite Elements

BANQUET

6:30-10:00 PM  Banquet Dinner
Great Hall of the Bancroft Hotel (corner of College and Bancroft Avenues, directly across from the campus.)
Speaker: K. S. Pister
SATURDAY - MAY 11, 2002

TECHNICAL SESSIONS

8:00-8:30 AM  Continental Breakfast  
Garbarini Lounge (outside Sibley Auditorium)

8:30-10:00 AM  Session 5 - Experimental Simulation  
J. G. Bouwkamp (Session Chair), Experimental Simulation  
F. Seible, Large/Full-Scale Laboratory Validation of Seismic Bridge Response  
M. A. Sozen, The Clough-Penzien Paradox  
P. Hidalgo, Earthquake Engineering in Chile: From the 60’s Until Now

10:00-10:30 AM  Break

10:30-12:00 PM  Session 6 - Structural Design and Retrofit  
V. V. Bertero (Session Chair), Contributions of Professors Clough and Penzien to Current Trends in Structural Design and Retrofit  
S.-L. Lee, Wind Load Design of Tall Buildings  
K. Kawashima, Effects of Pounding and Restrainers on the Seismic Response of Bridges  
R. D. Hanson, Evaluation and Repair of Earthquake Damaged Buildings  
J. E. Roberts, Caltrans Seismic Design Philosophy

12:00-1:30 PM  Lunch  
Served on the Bechtel Plaza, outside, adjacent to Sibley Auditorium

1:30-3:20 PM  Session 7 - Special Structures  
M. Agbabian (Session Chair), An Overview of Special Structures  
I. Katayama, HASSI and SSI Analysis of Heavy Structures  
R. A. Imbsen, The Contributions of Joseph Penzien and Ray Clough to Bridge Design Methodology Following the San Fernando Earthquake  
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Z. Guando & C. Houqun, Cordial Friendship and Successful Cooperation in Honor of Professor Ray W. Clough

3:20-3:45 PM  Break

3:45-5:15 PM  Session 8 - Emerging Technologies  
S. C. Liu (Session Chair), Recent Research in Sensors and Smart Structures Technology  
T. Kobori, The New Phase of Structural Control  
G. L. Fenves, The OpenSees Software Framework for Earthquake Engineering  
K. Pister, Structural Monitoring with Smart Dust

5:15-5:30 PM  Closing Session  
A. Der Kiureghian
Session 1:
Dynamics of Structures
Anil K. Chopra  
*University of California, Berkeley*

**Ray Clough and Joseph Penzien: My Mentors**

I am delighted to participate in this Symposium. Ray Clough and Joe Penzien have had more influence on my professional growth than anybody else. My career has benefited in incalculable ways from Joe and Ray. Almost my guardian angels if you will, they offered opportunities and encouragement at precisely the most critical junctures in my career.

My professional and personal relationship with Ray goes back to April 1961, when I, a 20-year old kid in India, received a letter from him offering me a teaching assistantship at $225/month. This letter changed my life. But for Ray’s letter, I would have spent my life in India, perhaps happy, but in no way having had the exhilarating and personally satisfying career I have had to date. I made this exact statement at the occasion of Ray’s retirement. I was truly shocked when Ray casually mentioned that he had offered me that teaching assistantship contrary to University policy, which at that time excluded foreign students from such positions. Ray, thanks for taking a chance on me.

I started as a graduate student at Berkeley in the Fall of 1961 and in Spring of 1962 took the graduate course in Dynamics of Structures. Ray was the instructor for the first half of the course. Then he left for a UNESCO seismological mission to the Mediterranean and the Middle East, and Joe taught the latter half. I learned structural dynamics and earthquake engineering from both of them.

Under Joe’s supervision, my research for the Master’s degree addressed a problem suggested by John Blume’s consulting office. They were designing a small addition for the top of an existing building in San Francisco. Neither Joe nor I can recall the nature of this addition, but I do remember that we found that the natural vibration frequency of this light appendage was close to the fundamental frequency of the building. We realized that we’d better be careful. The goal was to develop a response spectrum analysis procedure for calculating the seismic demands on the appendage. My modest accomplishment led to a Master’s thesis and a paper with Joe Penzien, my first published paper. We computed what seemed like unbelievably large forces in the appendage when it was tuned to the building. These results were vindicated when a few months later the 1964 Great Alaskan earthquake destroyed penthouses on top of buildings that were only lightly damaged. This project with Joe got me interested in earthquake engineering.
About that time, Berkeley received perhaps the first major research grant in earthquake engineering. Funded by the State of California’s Department of Water Resources, the project was concerned with seismic analysis of earth dams. Ray Clough, Joe Penzien, and Harry Seed were the Principal Investigators. Once again, their faith in me unwavering, Ray and Joe offered me a golden opportunity to work on this project. This became the basis for my Ph.D. research. It led to one of the early applications of the finite element method to earthquake analysis of continua. Using constant-strain triangular elements we computed vibration properties and earthquake-induced stresses in the dam.

Ray, who was my thesis supervisor, thought my completed work on finite element analysis of embankment dams was sufficient for a Ph.D. dissertation. In those days I was a complete math nut. Ray humored me while I looked for a problem where I could write some complicated-looking equations and found one related to my thesis topic. I stumbled upon Westergaard’s classic paper (1933) analyzing hydrodynamic pressures on a rigid dam. I found I could solve the wave equation and determine the pressures on the dam in the frequency domain, analytically transform the complex frequency response function to the unit impulse response, and then evaluate the convolution integral for numerically-defined ground motion, horizontal and vertical components. Realizing that this work was limited by its assumption of a rigid dam pointed to the need for including dam-water interaction in the analysis.

Ray and Joe’s mentorship continued for many years beyond my student days. After I joined the Berkeley faculty, they lent their names to a research proposal on earthquake analysis of concrete dams I wanted to submit to the U.S. Army Corps of Engineers. After the proposal was funded, in their typically generous fashion, they turned the project over to me, opening the door for my research on earthquake analysis of dams, including dam-water-foundation interaction.

I would need a lot more time to talk about Ray and Joe’s many significant contributions to structural dynamics. However, I do wish to underscore the importance of their book, *Dynamics of Structures*, which was published in 1975. Translated into Chinese, Greek, French, Japanese, and Russian, it was a landmark book in terms of its broad scope, comprehensive coverage, and philosophy. Several generations of students and engineers in the United States and abroad learned the subject from this very book.

In closing, I am delighted to have this opportunity to express my deep appreciation for the influence Ray Clough and Joe Penzien have had on my professional growth and my profound admiration for their contributions to structural dynamics and earthquake engineering. These contributions only pale when compared to the camaraderie, generosity, and spirit of collaboration that were hallmarks of their careers here at Berkeley. In these rough and tumble days of academia where funding is scarce and competition fierce, I am extremely grateful to have had their unwavering support. Those were truly magical days that I doubt will ever be repeated, with Joe and Ray the head magicians, waving their wands to create a research and academic environment that put the Earthquake Engineering Research Center on the map forever as the foremost institution for earthquake engineering in the world.
Dynamic analyses of structures were traditionally performed in the time domain, using modal analysis or direct integration of the equations of motion (particularly for nonlinear problems). In other areas, however, dynamic solutions were normally obtained as a function of frequency for a steady state harmonic excitation. So, for instance, in soil dynamics, the dynamic stiffnesses of foundations (for vibrating machinery) were always obtained as complex functions of frequency; and in fluid dynamics MacCamy and Fuchs had found an exact solution for the linear hydrodynamic forces acting on a rigid vertical cylinder as a function of frequency as early as 1954, using potential (diffraction) theory. The formulation of structural dynamics problems in the frequency domain gained some popularity in the 70’s in relation to seismic soil-structure interaction and fluid-structure interaction problems (for large diameter bodies such as the gravity offshore platforms of the North Sea). This popularity was due in part to some of the advantages of this kind of formulation but was made possible primarily by the development of the Fast Fourier Transform algorithms and computer software. The main advantages of this formulation were that it allowed one to obtain analytical solutions for systems with distributed mass; that it allowed to consider unbounded domains; and that it provided an easy way to account for a stochastic description of the excitation and to obtain as a result statistical measures of the structural response. The definition of wave kinematics and forces in terms of a power spectrum (including unidirectional and multidirectional waves) had been a standard procedure for a number of years. The definition of seismic motions in spectral terms was on the other hand a new development. The formulation for a continuous member with distributed mass, including effects of shear deformation and rotatory inertia as well as a constant axial load was already included in the first edition of Clough and Penzien’s textbook on *Dynamics of Structures*, published in 1975, as were the bases for dynamic analyses in the frequency domain of single degree of freedom systems under stochastic excitation. The complete frequency domain analysis procedure for general systems was presented in the second edition.
The classical formulation in the frequency domain was only strictly applicable to linear problems and this was a serious limitation. Nonlinear soil behavior was simulated in soil-structure interaction analyses using an approximate and rather crude iterative scheme, which became however very popular and is still used extensively today. Nonlinear effects due to the convective acceleration, the free surface boundary conditions, the variation in the wetted surface with the passage of the waves, and the computation of the hydrodynamic forces in the displaced position of the structure were accounted for, on the other hand, using perturbation theory and introducing quadratic and even cubic transfer functions. This led to second order and third order diffraction theories. The use of third or higher order terms for a complete diffraction analysis becomes, however, very cumbersome. Yet these higher order transfer functions (or Volterra kernels) are very useful in the physical interpretation of experimental data (obtained for instance in wave basins or in the ocean) to isolate and identify the different types of nonlinearities present in a particular problem. This approach has started to be used in soil amplification studies recently but, unfortunately, it has not seen yet any serious applications in structural dynamics.

The above limitations decreased for a few years the popularity of frequency domain solutions and led again to the use of time domain formulations for nonlinear problems, increasing at times the accuracy in the modeling of the nonlinear behavior at the expense of introducing approximations in other aspects of the model. More recently analyses in the frequency domain have seen a resurgence of interest for a series of new applications:

- Nondestructive testing of structural elements, structures as a whole, soil deposits, and pavements to determine their elastic properties in situ or to identify damage and its location relies often on dynamic testing for very low amplitudes of vibration, with essentially linear behavior. Interpretation of the data requires more accurate dynamic analyses accounting for distributed masses and wave propagation details.

- A series of new techniques to study transient or evolutionary processes using time-frequency decompositions (wavelets, periodograms, etc.) are providing valuable insight into the characteristics of nonlinear dynamic systems and the evolution of various nonlinear effects with time.

- Damage to bridge piers during the Northridge and Kobe Earthquakes has renewed the interest in assessing the potential effect of vertical ground accelerations, particularly when there are high frequency components that may generate large amplifications. An accurate determination of these effects requires accounting for distributed masses or discretizing each element into various components using consistent masses. Frequency domain analyses can provide exact solutions, including all wave propagation effects in the linear range, and thus benchmarks to evaluate the accuracy of other models (to be used with nonlinear analyses).
For many years, the Ductility Factor method has been used in seismic codes. The basic assumption of this method is that the deformations of a structure produced by a given ground motion are essentially the same, whether the structure responds elastically or yields significantly. This assumption represents the “equal displacement rule,” originally proposed by Veletsos and Newmark. A lot of research has been done in last four decades on the relations between elastic and inelastic demand quantities. Results differ depending on the set of ground motions and on the structural characteristics used in statistical studies. However, extensive research has not devalued the simple equal displacement rule. On the contrary, at least for SDOF structures on firm sites with the fundamental period in the medium- (velocity controlled) or long-period (displacement controlled) range, with relatively stable and full hysteretic loops, the equal displacement rule has proved to be an adequate assumption.

Using the equal displacement rule, the ductility dependent reduction (response modification) factor $R_u$ is equal to the ductility factor. The simple chart, provided in the first edition of Clough-Penzien’s *Dynamics of Structures* (Fig.1) is essential for understanding the concept of reduction factors and of the Ductility Factor Method. In the second edition of the book, the Ductility factor method and Fig.1 disappeared. Nevertheless, the author is still a fan of this figure. The educational value of the figure can be largely increased by using the acceleration-displacement (AD) format, introduced by Freeman. In AD format, Fig.1 (force has to be divided by mass) can be combined with demand spectra (Fig.2). Fig.2 resembles the basic chart in the Capacity Spectrum Method. The main difference is in inelastic demand, which is defined by an inelastic spectrum rather than by an equivalent highly damped elastic spectrum, which is the controversial part of the original Capacity Spectrum Method. The inelastic spectrum in the medium- and long-period range in Fig.2 is based on the equal displacement rule.

In Fig.2 the quantities relevant for the seismic response of an ideal elasto-plastic SDOF system can be visualized. Seismic demand is expressed in terms of accelerations and displacements, which are the basic quantities controlling the seismic response. Demand is compared with the capacity of the structure expressed by the same quantities. Fig.2 helps to understand the relations between the basic quantities and to appreciate the effects of changes of parameters. The intersection of the radial line corresponding to the elastic period of the idealised bilinear system $T$ with the elastic demand spectrum $A_e$ defines the acceleration demand (strength) required for elastic behaviour, and the corresponding elastic displacement demand $D_e$. The yield acceleration $A_y$ represents both the acceleration demand and capacity of the inelastic system. The reduction factor $R_u$ is equal to the ratio between the accelerations corresponding to elastic $(A_e)$ and inelastic systems $(A_y)$. If the elastic period $T$ is larger than or equal to $T_c$, which is the characteristic period of ground motion, the equal displacement rule applies and the inelastic displacement
demand $D$ is equal to the elastic displacement demand $D_e$. From triangles in Figs.1 and 2 it follows that the ductility demand $\mu$ is equal to $R \mu$. Fig.2 also demonstrates that the displacements $D_d$ obtained from elastic analysis with reduced seismic forces, corresponding to design acceleration $A_d$, have to be multiplied by the reduction factor $R$, which is the product of $R \mu$ and overstrength factor, defined as $A_y/A_d$. The intersection of the capacity curve and the demand spectrum provides an estimate of the inelastic acceleration and displacement demand, as in the Capacity Spectrum Method. This feature allows the extension of the visualization to more complex cases, in which different relations between elastic and inelastic quantities and different idealizations of capacity curves are used. However, in such cases the simplicity of relations, which is of paramount importance for practical design, is lost. Note that Fig.2 does not apply to short-period structures.

Fig.2 can be used for both traditional force-based design as well as for the increasingly popular deformation-controlled (or displacement-based) design. In these two approaches, different quantities are chosen at the beginning. Let us assume that the approximate mass is known. The usual force-based design typically starts by assuming the stiffness (which defines the period) and the approximate global ductility capacity. The seismic forces (defining the strength) are then determined, and finally displacement demand is calculated. In direct displacement-based design, the starting points are typically displacement and/or ductility demands. The quantities to be determined are stiffness and strength. The third possibility is a performance evaluation procedure, in which the strength and the stiffness (period) of the structure being analysed are known, whereas the displacement and ductility demands are calculated. Note that, in all cases, the strength corresponds to the actual strength and not to the design base shear according to seismic codes, which is in all practical cases less than the actual strength. Note also that stiffness and strength are usually related quantities. All approaches can be easily visualised with the help of Fig. 2.

Recently, incremental dynamic analysis (IDA) has emerged. An IDA curve, which relates first mode spectral acceleration with displacement, is shown in Fig.2 represented by the radial line corresponding to the period $T$, if the equal displacement rule is used.

The relations apply to SDOF systems. However, they can be used also for a large class of MDOF systems, which can be adequately represented by equivalent SDOF systems. The combination with the nonlinear pushover analysis substantially increases the accuracy of the procedure compared to the traditional Ductility Factor Method.

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**Figure1:** Figure from the 1st edition of the Dynamic of Structures.

**Figure2:** Elastic and inelastic demand spectra versus capacity curve.
The role of dynamics of structures in earthquake engineering of bridges was not fully recognized until the 1971 San Fernando, California earthquake during which many bridges collapsed due to vibratory response of the bridge structures produced by ground shaking. Immediately following that earthquake, a research program entitled, “An Investigation of the Effectiveness of Existing Bridge Design Methodology in Providing Adequate Structural Resistance to Seismic Disturbances,” was launched in the UC Berkeley Earthquake Engineering Research Center (EERC) under the technical supervision of Professors Joseph Penzien, Ray Clough, and William Godden. The program was sponsored by the Federal Highway Administration (FHWA) and lasted for almost 10 years. It was the beginning of the application of the modern principles and theories of structural dynamics to bridge engineering and it set the course of the subsequent development in the last two decades. Since this initial program, the theories of dynamics of structures, with ever broader and more sophisticated applications, have played a central role in the development of today’s earthquake engineering practice for bridge structures.

Although rather sophisticated nonlinear time-history dynamic analysis methods were developed in the initial research program cited above, the full appreciation and application of these methods was not realized until some 20 years later, after the 1989 Loma Prieta and 1994 Northridge, California earthquakes. Like the building codes adopted in the period from about 1975 to 1990, the application of the theories of structural dynamics to bridge earthquake engineering had focused mainly on use of the linear modal-superposition dynamic analysis method in conjunction with the seismic input of earthquake response spectra. Nonlinear effects of inelastic deformation and ductility on seismic response of bridge structures were not explicitly considered in dynamic analysis but were taken into consideration after the analysis was performed by use of force reduction factors similar to those used in the building codes for ordinary building structures.

During about the same time period, the role of soil dynamics and dynamic soil-structure interaction (SSI) on seismic response of structures started receiving much attention, and efforts had begun on development of site response and SSI analysis methodologies. During the late 1980’s, an extensive field model experimental program was carried out by the nuclear power industry in Lotung, Taiwan, under the joint sponsorship of Electric Power Research Institute (EPRI), Taiwan Power Company (TPC), and the U. S. Nuclear Regulatory Commission (NRC). The results obtained from this experimental program confirmed the effect of site response on the near-surface earthquake ground motions. Furthermore, the experimental results also confirmed the validity of the one-dimensional theory of wave propagation for predicting site response and the validity of various methodologies developed for analysis of SSI effects on seismic response of structures. Professor Penzien played a key role in promoting and assisting in planning the program, assisting in designing the experimental model structure, and participating in subsequent correlation studies using the experimental results of the program.
In the same timeframe, the SMART-1 strong-motion instrument array was also deployed in Lotung, Taiwan. Professor Joseph Penzien and Professor Bruce Bolt spearheaded the deployment of this array in cooperation with the Institute of Earth Sciences (IES) in Taiwan. The earthquake data obtained from the recordings of this array had shed much light on the characteristics of spatial variation of ground motions during earthquakes. Through statistical analyses, empirical equations for characterizing spatial variation of earthquake ground motions were developed. The data obtained from this program contributed greatly to an in-depth understanding and a better definition of earthquake ground motions for use in earthquake engineering of structures, including bridge structures.

In addition to the research efforts cited above, the findings and recommendations of the Governor’s Board of Inquiry on the 1989 Loma Prieta Earthquake, as published in the report entitled, “Competing against Time,” had made a profound impact on today’s earthquake engineering practice for bridges. Professor Penzien served as the Vice-Chairman of that Board. The report specifically recommended conducting formal seismic hazard analyses, developing design earthquake ground-motion time histories with incorporation of spatial variation characteristics, conducting site response analysis to account for local soil amplification effects, evaluating explicitly the soil-foundation-structure-interaction (SFSI) effects, and conducting rigorous nonlinear time-history dynamic response analysis for each important bridge. The evaluation of seismic vulnerabilities and the subsequent detailed design of seismic retrofit measures for the state-owned toll bridges in California being carried out by Caltrans since 1995 have implemented almost all of the recommendations contained in that report.

All the development efforts cited above have contributed to shaping earthquake engineering practice for bridges today. At the heart of this development, the theories of dynamics of structures provided the critically needed analytical framework.

The presentation outlined herein will focus on discussions of the role that dynamics of structures has played in the development of today’s earthquake engineering practice for bridges and the influences that Professors Clough and Penzien have made during the course of this development. Some examples derived from actual bridge engineering projects are presented to illustrate the application of the development at each stage.
A Simple Approximation For The Drift Spectrum

The elastic drift spectrum displays the story drift ratio (expressed as the ratio of the story drift to story height) that a ground motion record would cause in a multistory framed building as a function of the period of that building. It is a pivotal instrument for performance-based earthquake engineering. Wave theory for a uniform shear beam is utilized for calculating this spectrum in a rigorous way, but this requires that records of the ground velocity and displacement should be available. Alternative but less rigorous expressions of the drift spectrum for the ground story level of a multistory frame are developed. This set of formulations requires only that the displacement spectrum, or equivalently the acceleration spectrum, for which the basic input is the ground acceleration, should be at hand. I compare these expressions against both the rigorous formulation and other simple techniques. The error that the proposed formulation represents appears to be acceptable even when the comparison is done for near-field accelerograms where the drift demand is substantial.

Key words: Drift spectrum; Performance-based design; Shear beam; Wave velocity

P.S.

I was introduced to the broad field of earthquake engineering through the early seminal papers written by pioneers of this field. One such paper was Ray Clough’s “Dynamic Effects of Earthquakes” that was featured also in the AISC reconnaissance report on the Agadir, Morocco earthquake of 1960 where Ray had been a member of the investigating team. As with all of his other articles I was struck by the lucidity of his reasoning and the measured brevity of his description of how one could understand observed damage in buildings using the basic principles of structural dynamics. My later acquaintance of him and Joe has only increased my admiration of the inimitable style with which they helped elevate this branch of science to where it now stands.
Session 2:
Finite Element Method
A Small Subset of Finite Element Students

It is my privilege to be one of the co-chairs for the Finite Element Session of the Symposium honoring Ray Clough and Joe Penzien. My responsibility is to introduce the speakers and to make sure they stay within their assigned time limits. Since all speakers are very successful with impressive résumés, I could use all the allocated time for the session to introduce the speakers. Therefore, at this time I will only say a few words about each of these former CAL students, in the order they received their degrees.

My co-chair, Kurt Gerstle, was Ray Clough’s first graduate student at Berkeley and received his MS degree in 1952. He is now retired from the Civil Engineering Department at the University of Colorado.

Under the direction of Ray, I completed an MS in 1958 and a D. Eng. in 1963. My work included the development of the first automated finite element program.

Dr. Joe Rashid received his Ph.D. with Karl Pister and Ray Clough in 1964 on the application of the Finite Element Method to the Analysis of Axisymmetric Solids. After working in the nuclear reactor field for several years he founded Anatech Research Corporation.

Carlos Filippa received his Ph.D. with Ray in 1966. After a post-doctorial position at Berkeley, he worked in the research and development groups at Boeing and Lockheed. Approximately 15 years ago he was appointed as a Professor in the newly formed Department for Aerospace Structures at the University of Colorado.

Kasper Willam received his Ph.D. in 1969 and was part of the Scordelis, Clough and Wilson research machine. He will talk about being a student at Berkeley during the golden sixties and some of his recent research on civil engineering structures as a Professor at the University of Colorado.

Pål Bergan received his Ph.D. with Ray in 1971. He will talk about early finite element research and why so many Norwegian students selected Berkeley for their graduate studies.

Klaus-Jürgen Bathe worked with Ray and myself and received his Ph.D. in 1971 on numerical methods for the solution of eigenvalue problems. During 1972 and 74 he worked on a research project at Berkeley and developed a general nonlinear finite element program, which is now known as ADINA. In 1975 he joined the Mechanical Engineering Department at MIT.

We will start the session with Kurt and a Little History of the Finite Element Method.
The Finite Element Method – A Little History

We present a short history of the early days of the finite element method, its introduction and early application, and Professor Clough’s role in its development, in terms of some of the important publications of Clough, his colleagues, and his students.

Pre-computer methods such as model analysis and framework approaches are described, followed by the path-breaking paper by Argyris and Kelsey, which introduced matrix formulation and clearly established the duality between force and displacement methods. Application of computer-based methods to aero-space structures in 1956, and to conventional civil-engineering structures in 1960, coincided with developing computer capability. Possibly the first real-life civil engineering application of the finite-element method was in the investigation of a cracked dam in 1961, by which time this method had become mainstream in the profession.

This contribution concludes with grateful recognition of the great and life-long friendships between Ray Clough and his many students.
In over three decades of nearly uninterrupted development, the state of the art of finite-element-based constitutive and computational modeling of concrete structures has achieved the requisite level of maturity needed for the safety evaluation of lifeline structures. To illustrate this level of development, the presentation will draw on recent applications, which include: cyclic tests of bridge columns and knee joints from the seismic retrofit program in California, shaking-table tests of reactor containment models in Japan, shaking-table tests of multi-story building models in France, spent-fuel cask drop tests onto slabs-on-grade in England, and incremental construction and remediation of dams and locks for the Army Corps of Engineers. These examples are specially selected to cover diverse behavior regimes, ranging from the predominantly continuum class, which conforms to the classic finite element methodology, to the predominantly flexural type which does not quite fit traditional finite element formulation.

In bridge applications, greater developmental challenges were faced in adapting a fundamentally continuum-based approach to flexure-dominant inherently non-linear concrete structures. The point of transition of finite-element-based development to concrete flexural systems was the Loma Prieta Earthquake of 1989. Data from seismic retrofit experimental research programs sponsored by Caltrans at University of California campuses at Berkeley and San Diego contributed in a major way to the adaptation of continuum-based material and computational modeling to concrete bridge structures, the major challenges being concrete crushing, rebar-concrete interaction leading to shear failure, and computational stability at large deformations. Several examples illustrating the level of development in this area will be presented and discussed.

Coincidentally with the seismic research activities in California, and partially motivated by the Kobe Earthquake of 1995, an experimental/analytical collaborative research program was conducted by NUPEC, a research arm of the nuclear power industry in Japan, and the USNRC. The program consisted of shake-table tests of two large-scale models of pre-stressed and reinforced reactor containments. The Japan-US program was aimed at evaluating safety margins, in contrast with the UC/Caltrans’ program, which dealt with actual failures and structural redesign. The two research programs dealt with two different classes of concrete structures, employing very different approaches for the experimental simulations of earthquake loading. In contrast to the quasi-static cyclic tests in the California program, the Japanese program used time-history simulations of strong-motion earthquakes in which the shaking-table energy input was progressively increased until failure occurred. The same analytical tool, however, was used in both programs, which provided a rare opportunity to assess the effectiveness and the general applicability of the analytical method over a wide range of concrete structural designs.
Concrete constitutive modeling is extensively covered in the literature and will not be described here. However, in examining the literature one finds it almost devoid of discussion of the computational difficulties involved, giving the impression that none exist. Experience has shown, however, that computational breakdown is routinely encountered in general-purpose codes, especially in the range of most interest, namely the determination of the structure’s ultimate capacity or ductility limit. Even if computational instability is circumvented, the results are often in serious disagreement with tests or expected behavior. This has contributed greatly to the mistrust by traditionalists in structural engineering practice of claims made for finite-element-based concrete structural analysis. The computational instabilities involved stem from the complex concrete-reinforcement interaction and the highly non-linear material behavior, which at the constitutive level may be well characterized, but which are neglected at the computational level. Without proper treatment of the coupling between the constitutive formulation and the computational algorithm, a viable solution cannot be achieved.

The emphasis in this presentation is on this aspect of the general problem, using the presented examples to illustrate the level of computational rigor that is needed, and which took many years of development to achieve. As will be discussed, the computational/constitutive coupling is almost benign for mass structures, highly demanding for quasi-static cyclic loading, and of critical importance for dynamic loading.
History of Matrix Structural Analysis, Act III: The Boeing-Berkeley Connection

The theme of this Symposium is to celebrate the lifelong accomplishments of Professors Ray Clough and Joseph Penzien. This session on the Finite Element Method honors the key contributions of Ray Clough as one of the founding fathers of FEM. One of the duties of a father is to pick a name, and this he did in the paper “The Finite Element Method in Plane Stress Analysis,” given at the 2nd ASCE Conference in Electronic Computation held in Pittsburgh on September 1960. So FEM, as a name, is nearly 42 years old: middle agish, not yet senior. But the “FEM seeding” began much earlier (by 1930) as noted below.

There is no question that FEM caused a revolution in computational mechanics and, more generally, simulation based modeling. One need only to browse Timoshenko’s “History of Strength of Materials,” published in 1953, and compare it with current engineering practice. But did FEM come out of the blue? Although a definitive account has yet to be written, it seems certain to come up as an adaptive morphing of older methods merged with new tools, concepts and devices. More specifically, the present FEM combines three ingredients: continuum-based models, the Direct Stiffness Method (DSM) framework, and the programmable digital computer. Brains, skeleton and muscle.

What are the precursors of the three ingredients? Discrete structural mechanics, matrix methods and human computers, respectively. Of these three I recently researched the story of Matrix Structural Analysis (MSA). The result was an essay in J. Computer and Structures, 79, 1313-1324, 2001. The narrative was configured as a play in three acts to sustain the reader’s attention through confusing periods. The acts highlight three milestones in MSA: (1) the 1934-35 Phil. Mag. papers by aeroelasticians A. R. Collar and W. J. Duncan from the National Physical Laboratory at Teddington, England; (2) John Argyris’ 1954-55 article series in Aircraft Engineering while a Professor at Imperial College, London; and Jon Turner’s definitive account of the DSM during 1959 to 64 while a manager at the Aero Space Division of The Boeing Company, Seattle, WA.

The milestones convey the fact that aeronautics and space took the lead in MSA after WWII. For an obvious reason: only large aerospace companies could afford the first-generation digital computers and support staff. Civil Engineering, which with Cross, Hrennikoff and Southwell had made serious headway in human-driven numerical methods, had fallen behind by 1955. And universities were not in a much better position: one computer per campus at the rich schools was the norm. But by the late 1960s the SESM Division of Berkeley’s Civil Engineering Department was an acknowledged national leader in computational mechanics. What contributed to the big change?
The overall quality of the faculty was no doubt a key factor. In the 1982 NRC doctoral program survey only five US programs reached the 2.5-σ threshold of 75. Berkeley’s CE department was one of them. But timing and fortune, in the form of Ray Clough’s Boeing-Berkeley connection, were also of the essence. The events that led to the seminal 1956 paper by Turner, Clough, Martin and Topp have been amply discussed in the FEM literature and need not be repeated here. That was the “good timing” part. “Fortune” was the early outcome at Boeing of the struggle of the DSM against the entrenched classical force methods. A spirited fight went on for two decades at major aerospace companies. By 1965 only Boeing and Bell, influenced by Turner and Gallagher, respectively, had made serious commitments to the DSM. The final victory only came a decade later.

Ray Clough had introduced the DSM at Berkeley where it made quick and unimpeded progress. Why? There were no competitors! The struggle gripping aerospace, which I encountered prima facie at Lockheed in the 1970s, never reached Civil Engineering, which as noted above was way behind. Additional factors contributed to the rapid recognition of SESM as leader: relevant applications such as the Norfork Dam, and early tradition of open software with publication of FEM codes in departmental reports. Outgoing graduate students took card boxes and tapes to all corners of the earth. Anybody familiar with the Linux phenomenon can attest to the grass-roots power of open source software. Even now the “Berkeley coding style” can be recognized in hundreds of codes in use around the world by consultants and small companies.

My personal recollection of the Berkeley days is still fresh. I arrived in Fall 1963 to do an M.S. in Civil, recruited by Vit Bertero. First shock in coursework was the computer (a venerable IBM 7090 that served the whole campus, with SESM being naturally the biggest user). A weird contraption called an IBM card was passed around Scordelis’ first class in MSA. We did MSA homeworks in SMIS, a matrix interpretative program created by Ed Wilson, who later joined the faculty. I supported myself as an RA destroying BART columns in the big AML test machine. After a year I had decided experimental work was not my bag. When Ray Clough came back in 1964 from his Cambridge sabbatical I became his Ph.D. student, following Ari Adini, Jim Tocher and Ed Wilson.

Before 1965, doctoral theses in FEM were sequential events. The newcomer inherited the card boxes and bookshelves of the outgoer. By 1966 computer-oriented activities had exploded. More faculty were involved. Besides Ray Clough, other faculty including J. G. Bouwkamp, Colin Brown, Joseph Penzien, Alex Scordelis and Ed Wilson were addressing applications in Structural Mechanics while Karl Pister, Egor Popov and Bob Taylor were looking at Applied Mechanics problems. Among students and visitors in computational mechanics I interacted with at the time I recall John Abel, Giles Cantin, Athol Carr, Anil Chopra, Bob Dunham, Jerry Goudreau, Ojars Greste, Phil Johnson, Ken Kavanagh, Mahmoud Khojasteh-Bahkt, Z. A. Lu, John Meek, Mehrdad Mehrain, Dave Murray, Bob Nickell, Joe Rashid, Stuart Pawsey, Mike Shears, Kaspar Willam and Saeed Yaghmai. During my professional life I interacted later with Pål Bergan (Clough’s last doctoral student in FEM), Klaus-Jürgen Bathe and Ranbir Sandhu. The point is that by 1966-67 computational mechanics at Berkeley had achieved critical mass and momentum. It continued to flourish even after Ray Clough decided to “retire from FEM” to devote full time to earthquake engineering research.

After a year and a half as a post-doc, I went to Boeing in May 1968 to join Jim Tocher’s Math Analysis unit. This was in the spirit of the Boeing-Berkeley connection, but now with the technology-transfer flow reversed. Those were, as the Chinese say, interesting times at both Berkeley and Boeing. Three decades later I would like to join all Symposium participants in honoring Ray Clough and Joseph Penzien for their influential contributions as researchers, educators and team leaders, and for their service to the engineering profession.
Finite Elements - Free Style

This Clough-Penzien Symposium provides an excellent opportunity to look back and reflect on my student years at UC Berkeley. There can be no doubt that the years spent studying and researching computational structural mechanics during the end of the sixties and beginning of the seventies were, at the time, most exciting and inspiring. However, with more than thirty years passing since then one can now be allowed to view this experience in a historical perspective. The teaching and research activities at the SESM group during the pioneering period of the Finite Element Method has undoubtedly had a tremendous impact which can be measured in many branches of industry as well as in training of future generations of engineers.

I consider myself to be a “fortunate among the fortunate” who came to Berkeley and had Professor Ray Clough as my research advisor. This was no coincidence, Ray Clough had already spent a sabbatical year in Trondheim during the late fifties and done “missionary work” for new computational methods (the term “Finite Elements” did not yet exist). Exchange of structural engineering researchers and students between Berkeley and Norway started soon thereafter.

One of the strongest traits of Ray Clough is that he combines real, practical engineering understanding with the ability to formulate physical behavior in a mathematical language that computers understand. His engineering approach to problem solving was strongly evident in what is often considered the first real “finite element paper” (M.J. Turner, R.W. Clough, H. C. Martin, and L. J. Topp, “Stiffness and deflection analysis of complex structures,” Journal of Aeronautical Sciences, 23 (1956), 805-823). This and later papers by Clough and his coworkers have become an important source of inspiration for researchers and users of the finite element method.
It is the dream of every serious finite researcher to come up with “the ultimate finite element,” be it for membranes, plates, shells or solids. Most of these dreams have ended, at best, with an infinitesimal improvement on already existing elements. Contrary to the situation 40-50 years ago, a well proven mathematical and variational basis is now available for finite element developers. Although variational requirements are absolute and must be complied with, they also represent a sort of “straight jacket” in the element development. In the spirit of Ray Clough this author took a new look at the finite element approach considering the stiffness matrix as a numerical operator which in fact is the only connector between the element and the number crunching in the computers. All “secrets” of an element must be hidden in this operator; that is, all properties ensuring convergence consistent with the variational principles, and all properties characterizing the element performance in terms of being really good or just mediocre, must represented by the stiffness terms. This way of looking at elements lead to the concept of the “individual element test” by Bergan and Hanssen. This test corresponds to the “patch test,” but it is expressed as direct, numerical constraints for the finite element stiffness matrix. It can be used as a condition for developing new elements as well as for testing existing elements.

On the basis of the individual element test one can imagine an approach in which elements are parameterized with a few terms that depend on the element geometry, the rest is automatically given by the constraint conditions. An alternative to this is a further development by Bergan and Nygård which has been termed the “free formulation.” In this approach the stiffness matrix is split into a “basic” stiffness shared by different elements of similar type, and a “higher order stiffness” which characterizes the element’s ability to model higher order deformation patterns. A large number of different elements have been developed using this approach. Several of these elements, particularly membrane and plate elements, have been derived in cooperation with Professor Carlos Felippa, one of Ray Clough’s many prominent students.

Some important industrial applications of the finite element method will be presented including a reminder that things can go very, very wrong if the analyst’s engineering understanding or finite element modeling experience is inadequate.
From Finite Elements to the Berkeley Connection

This brief presentation is intended to recognize the lasting impact of Professor Ray Clough in the finite element arena and to illustrate his influence on generations of graduate students. To this end, I will start with the early development of finite spar elements to model cellular aircraft systems. This topic dates back to the original research interests of Ray in the golden sixties to construct elements which are truly ‘finite’ and which capture the bending of web components endowed with drilling degrees of freedom. It was this topic which he introduced to me in 1966 within an independent study. I vividly remember the regular project meetings with him and his graduate students Carlos Felippa, Athol Carr, Phil Johnson and Giles Cantin in Naval Architecture I was privileged to participate in. It was Ray’s encouragement and patient guidance which motivated me to engage in the emerging world of finite elements developing stiffness matrices on the back of reams of computer printouts. This early effort resulted in a family of spar elements which were incorporated in the finite element program CELL for the analysis of box girder bridges, a project directed by Professor Scordelis with funding from CALTRANS.

One of the challenging aspects was the use of drilling degrees of freedom and Hermitian interpolants to capture the in-plane bending within spar elements which reproduce the web behavior of box structures within a single finite element. The underlying cubic beam expansion of the transverse displacements introduced quadratic in-plane displacements which required matching quadratic expansions of the contiguous deck elements. Thus the concept of ‘interdependent interpolation’ was created early on to avoid ‘locking.’ Similar arguments led later on to a flurry of publications on interdependent interpolation of transverse displacements and rotation fields when Mindlin shear theory of flexure is used to develop $C^0$-beam, plate and shell elements.

At the end of the sixties ‘reduced’ and ‘selective integration’ techniques emerged at UC Berkeley in the group led by Ray Clough as an alternative approach to remedy locking and to improve the performance of low order elements in a very cost-effective manner. In this context, I pursued selective integration in my thesis [Willam, 1969] and interpreted this pragmatic approach within the framework of mixed variational calculus using independent displacement and strain expansions. Thereby, the ‘Limitation Principle’ of de Veubeke provided guidance to constrain the strain field with interpolants of lower order than the displacement gradient field. This had the same effect as selective reduced integration improving the shear performance of low order elements.
This early work on cellular structures provided the background for subsequent efforts in the spirit of the Reissner-Mindlin shear theory of flexure, [Haefner & Willam, 1984] and the Cosserat theory of micropolar continua [Iordache & Willam, 1998]. The current presentation is an attempt to extend this work to ‘flexible connections’ in framed structures. Such a joint element has its origin in the original work on spar elements and is of immediate interest for simplified frame analysis in earthquake engineering. To this end, I assigned a midterm examination to my graduate class on ‘Finite Element Analysis of Structures’ this Spring Semester. The outcome of this friendly competition will be presented at the CUREE Symposium in Honor of Ray Clough and Joseph Penzien. The intent is to challenge the graduate students in the form of a take-home examination to develop a panel element that connects beam and column elements with three DOF at each of the four midside nodes. The connection element is based on Mindlin theory of interdependent displacement and rotation fields to be compared with traditional lattices of orthogonal beam elements with no shear deformations.

For the Symposium it remains to examine the benefit of the more sophisticated Cosserat theory as a basis for an internal connection element. In this context, we need to consider the loss of symmetry in the stress and strain measures which appear in micropolar continua. Thus, the internal energy is comprised not only of axial, bending and shear strain energies, but also of an additional energy contribution due to the loss of symmetry of stress and strain. For illustration we will consider an internal connection element which serves as a model problem to look at the effect of shear-flexible symmetric and non-symmetric strain energy contributions.

To conclude, I hope these remarks on ‘finite connection elements’ will be of interest to the earthquake engineering community. I chose this topic also because of the worldwide connection of Berkeley faculty and students which I am privileged to part of. In short, I am deeply honored to join the Symposium participants in recognizing Ray Clough and Joe Penzien for their leadership in finite elements and earthquake engineering, and for inspiring generations of graduate students through the Berkeley connection.
Key Challenges at 40 Years After

It is now a little over forty years ago that Ray W. Clough coined the name ‘finite element method’ in his landmark paper [1]. This name is now recognized in practically all engineering and scientific fields to stand for a modern and effective numerical procedure to solve analysis problems and simulate natural phenomena. Of course, he not only coined the name but also made numerous seminal contributions to the field of finite element analysis, too many to list here. In addition, he provided leadership to attract faculty and students whose impact is seen today in all finite element teaching, research, computer programs, and practice.

With four decades of developments, and finite element analysis now firmly established in industry and academia, it is surely appropriate to ask “What further major advances might still be undertaken in the field?” In this short talk, we briefly address this question by presenting eight key challenges for further developments [2].

Challenge 1. The automatic creation and solution of finite element models. Many advances have already been made in the development of procedures that, automatically, create finite element meshes and solve for the response for a given accuracy, but there are many further advances possible in algorithms, optimal finite element discretizations, error measures, utilizing advances in hardware, and in actual practical implementations.

Challenge 2. Effective finite element schemes for fluid flows. A large number of publications exist on the finite element analysis of fluid flows, but the schemes proposed are far from satisfactory. An ‘ideal’ solution scheme would be much more reliable and effective. It is likely that major advances are still possible.

Challenge 3. The development of an effective mesh-free finite element method. While much research has been expended on the development of meshless methods, only a few proposed techniques are truly meshless. An effective mesh-free method will greatly advance the field of analysis and it seems that such a method can be developed.

Challenge 4. The development of procedures for multi-physics problems. A major area of this kind is the analysis of incompressible and fully compressible fluid flows, including heat transfer, chemical and electro-magnetic effects, that are fully coupled to structures. Advances have been made in this field but significant further progress can be accomplished.
Challenge 5. *The development of multi-scale analysis procedures.* Many devices and phenomena in engineering and the sciences involve multiple scales. The spanning of scales in analysis of engineering designs, nano-technology, bio-medical applications, studies in earth sciences, to name just a few, provides a major challenge.

Challenge 6. *The modeling of uncertainties.* The purpose of an analysis is to model nature, as represented in a new design or an already existing system. However, invariably there are uncertainties and these ideally would directly be included in many analyses.

Challenge 7. *The analysis of complete life cycles of systems.* At present, largely, only the initial design of a system is analyzed and optimized; but there is need to develop ‘virtual laboratories’ in which complete life cycles of systems are optimized using simulations.

Challenge 8. *Education.* The powerful analysis tools are only of value if they are used with sound engineering and scientific judgment. This judgement must be created by a strong basic education in the universities and ongoing life-long education in practice.

The work on these (and, of course, additional) challenges will provide much further excitement in the field of analysis and will surely result in a ‘new level of mathematical modeling and numerical solution,’ as mentioned in reference [2]. This new level of analysis will increase tremendously the possibilities to design structures and systems, to study and understand nature – including ourselves – and thus will greatly enrich our lives.

References:


Session 3:
Strong Motion Seismology
Strong Motion Seismology—An Introduction

Strong motion seismology, or engineering seismology, is the field of study devoted to measuring, understanding and characterizing the features of strong ground shaking that are important to earthquake hazard reduction. Initiated in the 1920’s by John R. Freeman and other leading engineers, the strong-motion program of the U. S. Coast and Geodetic Survey recorded three accelerograms during the Long Beach Earthquake of March 10, 1933, including “…the first of its kind ever obtained within 20 miles of the point of the epicenter of a destructive earthquake” (Neumann, 1935). Significant records accumulated slowly, but by the 1950’s and early 1960’s, there were enough records that leading earthquake engineers, including Ray Clough and Joseph Penzien, could begin to study the important features of recording, processing and characterizing strong ground motion.

The first work in strong motion seismology by Professors Clough and Penzien was “Analysis of Earth Motion Accelerograms”, a joint effort that also included Victor Jenschke. It was distributed informally as one of the earliest of the famous series of reports from U. C. Berkeley’s Structural Engineering and Structural Mechanics Laboratory (Jenschke et. al., 1964). The report was the basis for more formal publications in the Bulletin of the Seismological Society of America and in the Proceedings of the Third World Conference on Earthquake Engineering. The questions addressed in these early studies included the base line correction needed in processing accelerograms, the corrections needed at high frequencies to correct for instrumental characteristics, the relations among the several types of response spectra, the non-stationary aspects of earthquake ground motion and the relation of spectral properties of ground motion to epicentral distance. Many of these questions, in forms modified by the accumulation of records and the advance of knowledge, are still important topics of research today.

In subsequent years Professors Penzien and Clough continued to study selected problems in strong motion seismology along with their more extensive work in structural analysis and response. Professor Penzien studied the three-dimensional characteristics of ground motion, both analytically, for example, by identification of principal axes of three-dimensional motion, and experimentally by a series of studies based on records from the SMART array in Taiwan. Professor Clough studied the nature of the excitation to Pacoima Dam implied by the famous Pacoima Dam accelerogram recorded near one of its abutments and the related problem of input mechanisms for extended structures like arch dams. Although not usually considered a work in strong motion seismology, their enormously successful textbook, Dynamics of Structures, published in 1975 and subsequently translated into Japanese, French, Chinese, Greek and Russian, has influenced an entire generation of earthquake engineers and strong motion seismologists (Clough and Penzien, 1975).
In this session we are going to hear several presentations on current topics of interest in strong motion seismology. I am sure that many of the presenters will be able to trace some of the roots of these topics back to earlier work of the two men we are honoring at this CUREE Symposium.

References


Hazard-Consistent Description of Seismic Force for Taiwan Seismic Codes

For the current development of seismic design code in Taiwan, the elastic seismic demand is represented by the design spectral response acceleration $S_{ad}$ corresponding to a uniform seismic hazard level of 10% probability of exceedance within 50 years (return period of 475 years). The Young-Coppersmith characteristics earthquake model was used on the re-assessment of PSH analysis in Taiwan. Fault slip rates are being used to constrain earthquake recurrence relationships of some active faults for site-specific PSH assessment. Based on the uniform hazard analysis, the mapped design 5% damped spectral response acceleration at short periods ($S^D_S$) and at 1 second ($S^D_1$) are determined for each administration unit of village, town or city level. These spectral response acceleration parameters were modified by site coefficients to include local site effects, and the site adjusted spectral response acceleration at short periods ($S^D_{DS}$) and at 1 second ($S^D_{D1}$) are expressed as

$$S^D_{DS} = F_a S^D_S; \quad S^D_{D1} = F_v S^D_1$$

where $F_a$ and $F_v$ are site coefficients. Based on the soil structures in the upper 30 meters below the ground surface, the site coefficients are determined. Finally, the seismic design base shear can be expressed as

$$V = \frac{S_{ad} IW}{1.4\alpha_y F_u} \quad \text{(for Buildings)}; \quad V = \frac{S_{ad} IW}{1.2\alpha_y F_u} \quad \text{(for Bridges)}$$

The constant 1.4 (for buildings) or 1.2 (for bridges) means the over strength factor between the ultimate and first yield forces, and it is dependent on the redundancy of the structural system.
To consider the effect of near-fault ground motion in seismic design, besides the consideration of characteristic earthquake model, the probabilistic analysis based on the seismic hazard analysis at a return period of 2500 years and the deterministic analysis based on the attenuation law corresponding to the maximum potential earthquake of the fault are also implemented. Based on the maximum potential magnitude of an active fault, the attenuation relations $S_{S,\text{Att}}(r)$ and $S_{1,\text{Att}}(r)$ for the median 5% damped spectral acceleration demands at short periods (e.g. 0.3 second period) and at 1 second are determined firstly. Compared with the mapped spectral response acceleration at short periods ($S^M_S$) and at 1 second ($S^M_1$) that are determined based on the uniform hazard analysis at a return period of 2500 years, the near-fault factors $N_A(r)$ and $N_v(r)$ can be defined as

$$N_A(r) = 1.5 \frac{S_{S,\text{Att}}(r)}{S^M_S}; \quad N_v(r) = 1.5 \frac{S_{1,\text{Att}}(r)}{S^M_1}$$

The factor of 1.5 implies the consideration of 1σ deviation of uncertainty of fault movement and the component effect (fault-normal). The site with either $N_A(r)$ or $N_v(r)$ larger than 1.0 is defined as the effect of near-fault ground motion on design spectrum.

To check the earthquake performance of designed structures, it is necessary to provide design ground motions which are compatible with the design response spectrum as specified by the seismic design code for a site of interest. The concept of group delay time is used to model the phase spectrum on each separated frequency range of ground acceleration according to the compact support of Meyer wavelet. The regression equations to predict the mean value and standard deviation of group delay times can be developed from the recorded seismic ground motion. Based on the predicted mean value and standard deviation for a target site, the sample of group delay time at a certain discrete frequency can be either generated randomly by a specified probability density function or simulated from the earthquake data observed at nearby stations by applying the Kalman filtering technique. Therefore, the phase spectrum can be modeled by integrating the simulated group delay times.

For the near-fault site, because of larger seismic demand caused by the near-fault effect, the maximum possible earthquake is defined at a uniform seismic hazard level of 2% probability of exceedance within 50 years (return period of 2500 years) and will be used for capacity check.
The earthquake simulator constructed at the Earthquake Engineering Research Center (EERC) of the University of California established under the leadership of Professors Clough and Penzien (Penzien, et al., 1967) produced research opportunities and major advances in earthquake resistant design, many of which are manifest in current provisions of the International Building Code (IBC). This presentation is the tale of the theory stimulated by one such research opportunity from its inception, when I was a graduate student at UCB, to its application herein to account for characteristics of site coefficients in the IBC. This tale in strong-motion seismology is but one small tribute in admiration of the giant contributions of Professors Clough and Penzien to earthquake engineering.

The testing of the first 50,000-pound hydraulic actuator in 1968, during Professor Penzien’s tenure as founding director of the EERC (Rea and Penzien, 1968), stimulated the development of the theory for 2 and 3 D viscoelastic wave propagation in layered media as an explanation of the seismic wave fields radiated by the actuator foundation. The initial support of Professor Penzien and suggestions by Professor Sachman, Rogers, and McEvilly led to theoretical solutions for a viscoelastic half space (Borcherdt, 1971). These and subsequent solutions for the reflection and refraction of P, Type I-S and Type-II S body waves, Rayleigh-type surface waves, and Love waves (Borcherdt, 1971, 1973, 1974, 1977, 1982; Silva 1976) predicted that several physical characteristics for 2D and 3D waves in layered media are distinct from those for elastic or 1D anelastic waves, including particle motions, velocities, damping, directions of energy flow, kinetic and potential energies, and energy flux. The theoretical solutions showed that refracted anelastic wave fields are in general inhomogeneous with characteristics, including velocity and attenuation that vary with refraction angle. Empirical and numerical results show that these characteristics of P and S waves, unique to anelasticity, are most distinctive in media or soils with significant amounts of damping and in wave propagation situations in which the degree of inhomogeneity of the wave fields is largest as might occur for wave fields incident at the edge of a basin or near critical refraction angles (Borcherdt, et al., 1985, 1986). Laboratory and subsequent field measurements helped confirm the theoretical predictions (Becker and Richardson, 1970; Borcherdt, et al., 1988, 1989) and explain previously unexplained empirical results in classic textbooks (Brekhovskikh, 1960).

As an application of the theory for this symposium, the solution for a viscoelastic soil layer over a rock half space is proposed as a theoretical basis to account for characteristics of site coefficients in the IBC. The dynamic response of a viscoelastic soil layer as calculated from closed form solutions using Mathematica is shown in Figure 1 for normally incident homogeneous Type–II S waves for damping ratios of 5 and 20% corresponding to different levels of input rock motion. Approximate site-class boundaries and site coefficients Fa and Fv as specified in the IBC are superimposed.
The theoretically predicted dependencies of $Fa$ and $Fv$ (Figs. 1a and 1b) on shear velocity and base acceleration or damping ratio are in good agreement with those in the IBC (Borcherdt, 1994; Seed, et al., 1994). The theoretical response of a site class E soil layer with a damping ratio of 10% as a function of angle of incidence (Fig.1c) shows that the response of the layer to an inhomogeneous wave field increases with increasing angle of incidence as might occur near basin margins. With the exception of this situation, the theoretical model suggests that $Fa$ and $Fv$ in the IBC conservatively account for the major average characteristics of the response. Recent empirical estimates of $Fa$ and $Fv$, as derived from the Northridge strong-motion recordings and $vS30$ measurements are consistent at the 95 percent confidence level with the IBC coefficients for base acceleration levels greater than about 0.25 g (Borcherdt, 2002). Hence, the closed form solutions as parameterized herein for a viscoelastic layer are proposed as a theoretical model for consideration in support of the site coefficients in the 2000 IBC and the 2001 edition of the ICC as a small token in tribute to Professors Clough and Penzien.

This tale of viscoelastic wave propagation theory for layered soil deposits could not have been told had it not been for the leadership provided by Professors Clough and Penzien and their colleagues in establishing a center of excellence in earthquake engineering research in the late sixties. The interest and support provided by Professor Penzien during the initial testing stages of the hydraulic actuator has led to a life-long friendship and mentorship that continues to provide guidance whether it be explaining complicated probabilistic formulations, the likely dynamic response of designs for the new east span of the San Francisco Oakland Bay Bridge, or steps to take in the right direction to improve the codes. Their contributions to earthquake engineering stand as a monument for future generations concerned with earthquake resistant design.

Figure 1: Theoretical responses of a viscoelastic soil layer to normally incident homogeneous Type-II S waves account for major characteristics of $Fa$ and $Fv$ as a function of site class and input amplitude as specified in the IBC (a, b). Theoretical response of a class E soil layer to inhomogeneous wave fields increases as angle of incidence increases suggesting a response that might occur for waves incident near basin margins.

The UC Berkeley - CUREE Symposium
in Honor of Ray Clough and Joseph Penzien
Velocity Pulses in Near-Fault Ground Motions

An important feature that sometimes occurs in near-fault ground motions is a large pulse in velocity. The terms “fling” and “directivity” have been used interchangeable to refer to large velocity pulses in near-fault ground motions; however, these terms have very different meanings and result in different types of velocity pulses.

Directivity is related to the direction of the fault rupture from extended faults. The directivity pulse is a result of constructive interference of long period SH waves generated from parts of the rupture located between the site and the hypocenter. The directivity pulse is strongest on the horizontal component that is perpendicular to the strike of the fault (called the fault normal component). In contrast, the fling is related to the permanent tectonic deformation at the site. The fling pulse is a result of this permanent tectonic deformation occurring over a time interval of several seconds (for large earthquakes). The fling pulse occurs on the component that is parallel to the slip direction and does not depend on the rupture direction.

For strike-slip earthquakes, the directivity and fling pulses will be naturally separated into the fault normal and fault parallel components, respectively, but for dip-slip earthquakes, the directivity and fling pulses will both occur on the fault normal component. This makes it more difficult to separate the directivity and fling effects for dip-slip faults.

Models for developing design ground motions including the effects of directivity have been developed by Somerville et al (1997) and Abrahamson (2000). In practice, fling has generally not been considered in the development of design ground motions. Only recently have multiple strong motion recordings with strong fling effects been available that have focused attention on this type of near-fault ground motion. The 1999 Kocaeli, Turkey and 1999 Chi-Chi, Taiwan earthquakes provided multiple strong motion recordings with strong fling effects. The recordings from Kocaeli included both directivity and fling effects, but the recordings from Chi-Chi the fling effects dominated the near-fault velocity seismograms.

This paper describes a method for incorporating fling into design ground motions. The fling time history is modeled by a single cycle of a sine wave for sites located close to the fault (e.g. within 10 km). This model has three parameters: the period of the sine wave, $T_{fling}$, amplitude of the sine wave, $A_{fling}$, and arrival time of the sine-wave ($t_1$) with respect to the vibratory ground motion.
The equation for the fling acceleration time history is

\[
Acc_{\text{fling}}(t) = \begin{cases} 
0 & \text{for } t \leq t_1 \\
A_{\text{fling}} \sin(\omega (t - t_1)) & \text{for } t_1 < t < t_1 + T_{\text{fling}} \\
0 & \text{for } t \geq t_1 + T_{\text{fling}} 
\end{cases}
\]

where \(\omega = \frac{2\pi}{T_{\text{fling}}}\). Models for the three parameters, \(T_{\text{fling}}\), \(A_{\text{fling}}\), and \(t_1\) are given below.

The acceleration amplitude is related to the amplitude of the tectonic deformation at the site, \(D_{\text{site}}\), by

\[
A_{\text{fling}}(\text{cm/s}^2) = \frac{D_{\text{site}} 2\pi}{T_{\text{fling}}^2}
\]

For large strike-slip faults, the median value of \(D_{\text{site}}\) as a function of magnitude and distance is modeled by

\[
\log_{10}(\hat{D}_{\text{site}}(M, R)) = (0.5M - 1.4) - \log_{10}(\pi) + \log_{10}\left(\frac{\pi}{2} \tan^{-1}(0.22R)\right)
\]

where \(R\) is the horizontal distance to the rupture and \(D\) is in cm. The standard deviation of \(\log_{10}(D_{\text{site}})\) is 0.29.

Assuming that the median slip-velocity is independent of magnitude, the median fling period \(T_{\text{fling}}\), is

\[
\log_{10}(\hat{T}_{\text{fling}}) = 0.5M - 3.0
\]

where \(T_{\text{fling}}\) is in seconds and the standard deviation of \(\log_{10}(T_{\text{fling}})\) is 0.15.

The arrival time of the fling with respect to the S-wave arrival was evaluated using empirical recordings and numerical simulations (Graves and Abrahamson, 2002). For sites located close to the fault (e.g. < 10 km), the arrival time of the fling is close to the arrival time of the S-waves. For more distant sites, the fling arrival becomes more emergent arriving between the P- and S-waves. For the development of design ground motions, the polarity of the S-wave velocity time history is selected such that there is constructive interference between the velocity from the fling and the S-waves.

References


Session 4:
Probabilistic Methods
A Statistical Model for a Certain Construction Material

I did my graduate work at Berkeley from 1959 to 1964. It was my good fortune to have Professor Joe Penzien as my thesis supervisor and Professor Ray Clough as my academic advisor. I took structural dynamics from Ray and random vibrations (the first time it was offered) from Joe. It was an exciting time. All fields of structural engineering and structural mechanics were rapidly developing and that of probabilistic methods was just beginning to come into being. It was, as it were, a new era, waiting to be born.

Much is known about the contributions of Joe and Ray to structural engineering, structural mechanics and earthquake engineering. Their works in these areas have brought them a measure of recognition, I dare say, attained by only a few. I should like to take this opportunity to mention just some of their most outstanding qualities that permanently imprinted on my mind and left an indelible influence upon me. First of all, I was greatly impressed and inspired by their singular dedication to their chosen fields of study. As a student, I wished I could one day be like them. In research, both of them placed a great deal of emphasis on engineering intuition and physical insight. While reviewing my research, Joe was able to spot a mistake without looking at derivations nor the calculations. While I was on sabbatical leave at Berkeley in 1990, Ray told me that he was concerned that indiscriminate use of finite element method may lead to erroneous results and felt that basic knowledge of mechanics was ever more important when the tendency is to rely on computer results. I would like to carry his remarks a step further. As computers become more and more powerful, it is well to remember that basic simple analytical models and methods may still be useful to check computer solutions, to help design experiments which are usually an onerous undertaking, and, in case computer simulation is employed, to serve as an interpretive tool.
The following is such a model. In a mix design, one of the important factors affecting properties of the mix is the amount of void space in the aggregates which is influenced by the distribution of size of the aggregates (gradation.) The mix designer must perform quite a number of experiments using different aggregate gradations to achieve the desired amount of void in the mix. An analytical tool to aid the design of such experiments has hitherto not been developed. In 1952, (M.E.Wise. Dense Random Packing of Unequal Spheres. Philips Research Reports, 7, 321-343, 1952) an analytical model was devised to determine geometrical properties of a pack of spheres whose radii are random. The model is now extended to overcome some of the restrictions imposed by the model. The idea underlying the model can be simply and briefly stated as follows. Consider a pack of spheres of different radii. Assume that the spheres touch each other (gapless dense packing.) By joining the centers of the spheres, a system of tetrahedrons is obtained. For each of the four spheres whose centers are the vertices of a particular tetrahedron, the volume of the sphere inside the tetrahedron can be determined by knowledge of solid geometry and spherical trigonometry. The difference of the volume of the tetrahedron and the sum of the volumes of the four spheres enclosed in the tetrahedron gives the volume of the void. Since the radii of the spheres are random, so is the void whose statistical properties can be obtained by standard methods of probability. In Vavrik et al (W.R.Vavrik, W.J.Pine, G. Huber, S.H. Carpenter and R. Bailey. The Bailey Method of Gradation Evaluation: The Influence of Aggregate Gradation and Packing Characteristics on Voids in the Mineral Aggregate. To appear in Vol.70 in the Proceedings of the Annual Meeting of the Association of Asphalt Paving Technologists held in 2000), the void ratios of 25 samples obtained by experiment are given. These void ratios and the mean void ratios obtained by the present statistical method are found to be in fair agreement. This suggests that the model can be used as a starting point for the development of a more versatile and accurate analytical model for use by the pavement engineering community.

Note: The need for an analytical model for the calculation of void ratio of aggregates in asphalt mix design was brought to my attention by my colleague Professor Paul Khosla of the transportation materials program at North Carolina State University.
Probabilistic Methods in Seismic Hazard Analysis and Optimal Seismic Design of Structures

Summarized below are the applications of probabilistic methods to two practical industrial problems; namely, (1) in the seismic hazard analysis for the safety assessment of nuclear power plants, and (2) in the evaluation of cost-effectiveness in the design of R/C buildings for earthquake resistance. Specific sample results are described in the seismic hazard analyses for three nuclear power plants in Taiwan, and the analysis of the cost optimal design of a steel-R/C building in Tokyo.

Introduction

Described below are two projects that the author had the privilege of working jointly with Professor Joseph Penzien over a period of about fifteen years. Although there was no similar opportunity with Professor Ray Clough, his work in finite element and earthquake engineering has greatly influenced the author’s own academic and professional career.

One project involves the probabilistic seismic hazard analysis for three nuclear power plants in Taiwan, called Plants #2, #3, and #1 located in Kuosheng, Maanshan, and Chinshan, respectively. The results of the analyses, in the form of hazard curves, for each of the plant sites were then used in the comprehensive seismic PRA (probabilistic risk assessment) of each plant. The other project involves the evaluation of the cost-effectiveness of designs of steel-reinforced concrete buildings in Japan. The latter project was conducted as part of the development of the in-house capability in structural dynamics and reliability-based design of structures at the Tokyo Electric Power Services, Co.
Probabilistic Seismic Hazard Analysis

Probabilistic analysis of seismic hazard was applied to define the earthquake ground motions at the sites of the three operating nuclear power plants in Taiwan. The studies were conducted in 1983 through 1992; first for Plant #2 in Kuosheng, under contract between the Eastern International Engineers, Inc. of Berkeley, California and the Atomic Energy Council of Taiwan. The same approach was applied subsequently to Plants #3 in Maanshan and #1 in Chinshan; these latter studies were conducted by a local team with the author and Professor Penzien serving as principal consultants. The probabilistic approach provides the framework for the systematic integration of available statistical and seismological data, geologic and tectonic information, and expert judgments leading to computational results of the probabilities of peak earthquake ground motions at the respective sites. The results of the analyses were then used in the subsequent probabilistic risk assessments of the three plants. Typical final results in terms of hazard curves are shown below in Fig. 1 for Plant #2 and in Fig. 2 for Plant #3.

Cost-Effective Design of SRC Buildings

Preliminary to the development of cost-effective designs of electrical power transmission systems for earthquake resistance, TEPSCO (Tokyo Electric Power Service, Co.) initiated a study to carefully analyze the cost-effectiveness of a specific SRC building that houses the headquarters of the company in Tokyo, Japan. The building was designed in the early 1990’s following the Japanese building code. Cost-effectiveness is defined relative to the minimum expected life-cycle cost of the building under earthquake loadings over the lifetime of the building.

The details of the study were carried out by the technical staff of TEPSCO under the leadership of Dr. I. Katayama, member of the Board of Directors of the company. The final results are shown in Figs. 3 and 4 below, indicating that the building, as designed and built according to current Japanese building code, is close to the minimum expected life-cycle cost within the range of discount rates assumed (1%-3%).

![Hazard Curves for Plants #2 & #3](image1)

![Life-Cycle Costs of SRC Building](image2)
Acceptance criteria for performance-based earthquake resistant design are ordinarily expressed in terms of upper bounds to the peak values of the system response variables that determine failure conditions for different limit states. For most failure modes of structural and non-structural elements, the response values of interest may be distortion amplitudes, local accelerations or local velocities. These values may be estimated by means of structural analysis methods with different levels of refinement and accuracy. For each limit state to be considered, the design condition is expected to be satisfied for a ground motion intensity associated with a pre-established return interval.

The ultimate objective of engineering design is to produce systems with optimum life-cycle performance. Within the context of earthquake-resistant design, this entails accounting for several sources of uncertainty. Some of them are associated with both the future seismic history and the detailed properties of the ground motion during each earthquake. Others are related to our imperfect knowledge about the mechanical properties of the systems of interest, the laws that govern their seismic response and performance, and the errors in the models used to predict them. Therefore, life-cycle performance must be expressed in terms of variables such as the failure probability during a time interval “t”, the expected failure rate per unit time, or a normalized value (with respect to the initial cost) of the expected cost of damage per unit time.

For practical reasons, the life-cycle objectives of performance-based design have to be indirectly accomplished by means of control variables and parameters that are referred to earthquakes of given intensities (associated with specified return intervals). This has created the need for criteria and algorithms to establish quantitative relations between the system vulnerability and reliability indicators for specific intensities and the corresponding life-cycle measures. But design rules for practical applications must simultaneously comply with the conditions of being easy to apply and leading to the required values of the reliability and vulnerability indicators, for each intensity as well as for the expected life cycle. This is an important challenge faced by the writers of performance-based seismic design recommendations.
Conventional models for the analysis of structural reliability are based on the assumption that failure of a system subjected to earthquake excitation occurs when the peak value of the deformation demand associated with the structural response exceeds the corresponding deformation capacity. For this purpose, both demand and capacity may be referred to the global response of the system or to that of the segment of it (for instance, a story of a building), where the safety margin reaches its lowest value. Probabilistic estimates of the relevant peak response amplitudes can be obtained, either through the use of a detailed model of the system or by resorting to simplified systems used in conjunction with sets of adequate transformation factors. The latter have to be treated as random variables, whose probability distributions have to be estimated from systematic studies about the responses of corresponding pairs of detailed and simplified models of a given system. Estimating lateral deformation capacities of complex nonlinear systems subjected to earthquake ground motion is much more complicated, however. The difficulties are largely due to the complexity of the collapse mechanisms and their sensitivity to both the system deformation pattern immediately before failure and the influence of damage accumulation due to cyclic response. For this reason, alternative formulations have been proposed that express the capacity of a system in terms of the intensity leading to its collapse. But the response of a nonlinear MDOF system to an earthquake of a given intensity may in general be sensitive to the detailed characteristics of the ground motion time history. Therefore, the intensity-based seismic capacity of a system will have to be handled as a random variable, even if the mechanical properties of the system are deterministically known. Two alternative approaches have been proposed to deal with this problem: the incremental dynamic analysis (IDA) and the stiffness-reduction damage model (SRDM). Both approaches provide a solution to the problem of estimating reliability and vulnerability indicators as functions of intensity, but both are computation-intensive. Their applicability to practical design will in general be conditioned to the possibility of establishing easy-to-use transformation rules between the responses predicted by them and those obtained by means of simplified models.

Probabilistic models of system response and performance that are suitable for practical applications are currently receiving significant attention, aiming at dealing with problems similar to those described above.
Arriving in Berkeley in 1978 as a young, aspiring assistant professor, two factors impressed me most. First was the openness and collegiality that senior faculty showed towards the junior faculty. At meetings and discussion forums, we were treated equally and encouraged to freely express our opinions. Equally important, everyone taught undergraduate as well as graduate courses, regardless of their seniority, and everyone got the chance to teach a graduate course in his or her area of research. This spirit of egalitarian democracy provided a tremendous boost to the junior faculty in finding their rightful positions within the department and in recruiting graduate students for their research.

The second factor I came to realize soon after my arrival at Berkeley was that I was on my own. At Berkeley, you did not work under a senior professor, who provided you research funding and also directed your research. You charted your career path on your own.

Ray Clough and Joe Penzien were true to these Berkeley traditions. They were supportive of the junior faculty, treated them as equal colleagues, and did not resent teaching undergraduate courses to allow the junior faculty to teach graduates. I remember how Joe offered me to teach his random vibrations course, as a way to help me recruit doctoral students. He also supported me in offering new courses in risk analysis and structural reliability. He was even instrumental in getting me started on a joint research project on lifelines with Professor Richard Barlow of IEOR Department. This introduction by Joe resulted in my many years of collaboration with Dick Barlow.

One of the important achievements of my early research was the development of the CQC modal combination rule. As the Editor of the *Journal of Earthquake Engineering and Structural Dynamics*, Ray realized the importance of this work and accepted to publish a short technical note co-authored with Ed Wilson in the *Journal* through a speedy process. That paper had a far-reaching influence, culminating in adoption of this rule by most codes of recommended practice. I also recall with fond memories a trip in the summer of 1982 to Skopje, Yugoslavia, with Ray, Shirley, Hugh McNiven and Mrs. McNiven. At that time I was traveling with an Iranian passport and needed a visa to enter most countries. Traveling from Skopje to Athens, we were stopped at the Greek border because my visa had expired, or more correctly, the Greek Consulate in San Francisco had stamped the wrong date in my visa. I recall how the Cloughs and the McNivens waited patiently and graciously in the car for almost two hours until my visa problem was resolved. This travel offered me the rare opportunity to know my senior colleagues and their spouses in a social setting. Their warmth and genuine friendship remains a high point in my memory of that trip.
I came to Berkeley with the mission to develop a teaching and research program in probabilistic methods. Joe had been a pioneer in this field with many important contributions, but he and the other faculty thought the time had come to enhance the SESM program in this area with additional courses in risk analysis and structural reliability. Starting from Ray’s pioneering work, Berkeley was the world leader in the finite element area, but no program existed in structural reliability. Very soon in my research, I realized the potential of combining finite element and probabilistic methods to develop a general-purpose framework for reliability analysis of complex structures. The first paper on this topic, co-authored with Bob Taylor, was presented in 1983 at the 4th ICASP conference in Florence, Italy. Since then, three students have completed their doctoral dissertations on this topic and many papers have been published. Below, I briefly describe our current work in this area. This topic nicely combines the two areas of finite elements and probabilistic methods that Ray Clough and Joe Penzien pioneered at UC Berkeley.

Under the sponsorship of NSF, a multi-university group of PEER researchers is developing an object-oriented, open-source framework for nonlinear structural and earthquake engineering analysis called OpenSees. Gregory Fenves, who leads the effort, will describe the broader scope of the project in his talk. My doctoral student Terje Haukaas and I are tasked in developing modules within OpenSees, which will allow: (a) sensitivity analysis of structural response with respect to material, load and geometric variables, (b) second-moment analysis aimed at assessing the propagation of uncertainties from input variables to response variables, and (c) analysis of structural reliability aimed at computing the probabilities associated with prescribed limit-states.

For sensitivity analysis, we have implemented a direct differentiation method, which involves developing and coding the derivatives of the governing equations in the finite element code. For the analysis of uncertainty propagation, we have used the well know first-order, second-moment approximation method to assess the response variance. For reliability analysis, we have implemented algorithms based on the first- and second-order reliability methods (FORM and SORM) and importance sampling. Example applications will be shown during the presentation.
Session 5:
Experimental Simulation
“Experimental Simulation – Numerical Simulation”
a UC Berkeley Perspective

In the first EERC report, entitled “Feasibility Study Large-Scale Earthquake Simulator Facility” (1967, Penzien, Bouwkamp, Clough and Rea), it was stated, that

“By far the greatest property loss caused by destructive earthquakes is that inflicted upon fixed structural systems such as buildings, bridges, dams, tunnels, aqueducts, etc. The formulation of a satisfactory method of designing such structures to withstand earthquake forces will require a tremendous amount of theoretical and experimental work. In recent years, the use of high-speed digital computers and the application of matrix algebra techniques have led to significant advances in analytical methods. However, since analysis involves the idealization of structural systems, it is difficult to relate the results obtained from analysis to the behavior of actual full-scale structures when subjected to strong earthquakes.”

The report subsequently notes the difficulties involved in establishing appropriate idealized numerical models of structures for damage prediction purposes and examines the damages caused on a number of buildings during the than recent Alaskan Earthquake of 1964. It comes to the conclusion, that with the state of knowledge at the time, it would have been impossible to formulate idealized structural models which could predict the damages observed. Also, the lack of knowledge of the force-deformation characteristics of certain structural elements as well as structural joints, contributing significantly to the observed damages, were noted. Hence, it was stated, that “the most urgent problem in structural engineering is the determination of the correct structural idealizations for various types of structures, and their force-deformation relationships under cyclic loading”.

In the conclusion of the report it was recommended that - before embarking on a large-scale table (30.5 m x 30.5 m in plan, weighing about 900 ton and cabable to test structures of up to 1,800 ton) - a program of development work be initiated covering the design of a suitable electro-hydraulic servo-system for the control of shaking tables capable of simulating several components of strong motion earthquake excitation and the construction of a medium-scale shaking table with the above servo-system to demonstrate the overall effectiveness and to allow studying experimentally the energy absorption characteristics of structural components, and assemblages under dynamic conditions. These feasibility studies led to the construction of the Earthquake Simulator Laboratory and the 6.10 m x 6.10 m shaking table at the Richmond Field Station.
In order to obtain information about the dynamic characteristics of full-scale structures on the one hand and allow the further development of computer modeling and programming techniques on the other hand, experimental work since the mid-sixties has been focused on full-scale, forced-vibration and (since 1971) ambient-vibration studies of high-rise buildings with different structural systems. Initially, moment and truss-frame systems, such as the San Francisco UC Medical Center Buildings (1968), the ALCOA Building (1971) and the Transamerica Pyramid Building (1973) were studied, comparing the experimental findings with analytical results using computer programs developed by Clough and later Wilson. Also, buildings with special layouts such as the in-plan triangular shaped Los Angeles Century City Building (1976), the pedestal-based Seattle Rainer Tower (1978) and the in-plan Y-shaped, Emeryville Pacific Park Plaza Building (1985) were tested to assess both the dynamic characteristics and computer modeling procedures. Also several prefabricated reinforced-masonry panel-type buildings as well as reinforced concrete panel, frame and slip-formed medium high-rise buildings were studied at Berkeley and, as part of a cooperative program between UCB and several Yugoslav Universities, in the former Yugoslavia. For the correlative studies the computer program TABS, operating as a segment within the SAP-80 Series of Programs, was developed specifically.

While the correlative effort of the above research activities resulted in a number of widely adopted computer programs, such as SAP 2000 and ETABS, the experimental research to define the cyclic nonlinear response of structural connections and assemblages and the effort to develop nonlinear computer programs to capture the observed response, have been an other major effort at UC since the early sixties. Specifically, the experimental work by Popov, Bertero and Mahin, using both quasi-static cyclic displacement-controlled as well as pseudo-dynamic testing techniques together with their efforts to formulate appropriate numerical models to reflect the observed nonlinear test results was paralleled by the work of Powell in developing nonlinear computer programs such as DRAIN 2D and ANSR-III, capable of predicting the non-linear response of structural systems under earthquake exposure.

Depending on the test objectives and test restrictions, the shaking table research effort in the first decades involved studying the dynamic response of numerous full-, medium- and small-scale models. These studies, many directed by Clough, were aimed at clarifying outstanding questions on the seismic response of different structural systems. Research covered, for instance, full-scale tests on masonry houses and various steel and concrete subassemblages. Medium-sized models of liquid storage tanks, multi-story steel braced and moment-resistant frames as well as concrete frames and shear-wall systems were studied to resolve specific seismic design aspects. Small-scale model studies on the fundamental performance of multi-span curved bridges as well as intake towers and submerged single and multiple storage reservoirs, thereby considering the structure-fluid interaction, were performed. Also the use of the shaking table in developing base isolation and energy absorbing devices should be noted.
Large/Full-Scale Laboratory Validation of Seismic Bridge Response

Seismic structural design/retrofit concepts and technologies are not just expected to ensure collapse prevention under the maximum design or safety evaluation earthquake but are also geared towards providing specific functional performance levels, damage control, and repairability for different earthquake intensities of ground shaking. While in the past, design and assessment models were aimed towards capturing some measure of the failure or collapse limit state, few of these models are capable of predicting actual performance levels for specific seismic events. Performance based seismic design concepts and multi-level seismic design codes require performance assessment and design models which capture the inelastic structural response of structural systems to earthquake ground motion input including damage accumulation, material uncertainties and variations in loading history. Only large or full-scale laboratory experiments can validate the applicability and usefulness of these performance assessment and design models.

Following each major earthquake in California with significant damage to the bridge inventory, such as San Fernando (’71), Loma Prieta (’89), and Northridge (’94), advances in seismic bridge design, retrofit technology development, and retrofit implementation for California’s bridge inventory accelerated. While flawed pre-71 design concepts and details were readily identified, appropriate retrofit measures and design approaches required new assessment and design models as well as validation of these tools, concepts and technologies to justify multi-billion dollar retrofit expenditures.
The experimental validation of these retrofit technologies can either be left to the next major earthquake or be accomplished through strategic one-of-a-kind large- or full-scale experiments in a controlled laboratory environment. These one-of-a-kind large scale tests are frequently termed “proof–tests,” since mostly proof-of-concept validation and model calibration are the principal objectives and not the development of a parametric performance data base.

Tests on structural components, subassemblages and/or complete systems are only meaningful as long as the input simulates actual seismic demands, the performance emulates damage patterns, accumulation and failure modes encountered in prototype structures, and the complete performance and structural response can be traced, measured, and documented. These objectives can only be met with tests which are (1) performed under controlled laboratory conditions to maximize quality data collection, (2) large or full-scale to exhibit representative damage patterns, accumulation and failure modes, and (3) performed under load/deformation simulations which represent actual seismic demands.

The presentation will focus on three such large or full-scale laboratory proof-of-concept tests in direct support of the Caltrans seismic bridge and retrofit program for (1) double-deck viaducts, (2) long span toll bridges, and (3) new advanced composite bridge systems.
The Clough and Penzien Paradox

In celebrating the stellar careers of two eminent engineers, it is proper to pose the question, “Why did Professors Clough and Penzien, who distinguished themselves by their contributions to the analytical process in engineering design, bother to spend time to experiment?”

If the actions of latter-day lights in analysis and of institutions responsible for research are to be taken as reflections of accumulated wisdom, the forays of Clough and Penzien into experimental analysis, however successful, would appear to be indiscretions.

In his 1930 essay, “One Hundred Fifty Years Advance in Structural Analysis,” Westergaard wrote, “Structural Analysis is, of course, intimately allied with and dependent on structural testing. The United States has excelled in the latter field. The grand scale of this experimental work, and the determination to find out, have aroused the admiration of Europeans. In structural engineering [The United States] has also excelled. In structural analysis, it has done well, yet the great ideas have come mainly from Europe.”

How could two researchers who helped turn the tables on Westergaard’s remark about the source continent of great ideas in structural analysis think it important to tinker with physical simulation of earthquakes in the laboratory and with testing of structural systems? Was it a lapse of judgment or did they know something that made them not pass this interest on to the students, engineers, and research support organizations that they influenced?

The paper will provide a distant view of the Clough-Penzien Paradox. Professors Clough and Penzien will be yielded time to account for their paradoxical acts if they so wish.

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Impact of U.S.-Japan Research Using Large-Scale Testing Facilities on Development of Pseudo Dynamic Testing

The pseudo dynamic test (also referred to as the online computer-controlled test or the online test) is an experimental technique for simulating the earthquake response of structures and structural components in the time domain. In this test, the structural system is represented as a discrete spring-mass system, and its dynamic response to earthquakes is solved numerically using direct integration. Unlike conventional direct integration algorithms, in the pseudo dynamic test the restoring forces of the system are not modeled but are directly measured from a test conducted in parallel with the direct integration.

The original concept of this test was proposed in the late 1960s (Hakuno et al. 1969), and the test in the present form, i.e., digital computation combined with quasi-static loading test, was established by the mid 1970s (Takanashi et al. 1975). Various efforts were made in the late 1970s and 1980s to refine the pseudo dynamic test and also to expand its capacity. Notable among these efforts are, pseudo dynamic tests on a very large scale (ACI 1985), pseudo dynamic tests controlling multiple degrees of freedom (DOFs) systems (ASCE 1989), and pseudo dynamic tests combined with the substructuring. Numerous problems surfaced out in the course of these applications, including problems of experimental errors leading to growth of erroneous responses, problems of scaling (size and rate-of-loading effects), and problems associated with integration algorithms that did not ensure unconditional stability in the online application. Many studies were carried out to overcome these problems and make the online test as a standard test procedure in earthquake engineering research. Summaries of these efforts are provided in Takanashi and Nakashima (1987) (for Japanese activities by the mid 1980s), Mahin et al. (1989) (for U.S. activities by the end of 1980s), and Shing et al. (1996) (for Japanese and US activities by the mid 1990s).

The development and application of the online test were conducted almost exclusively in Japan in 1970s and in Japan and the U.S. until the late 1980s. The potential of the pseudo dynamic test was recognized gradually in other countries, and in the 1990s many new developments and applications have been carried out in Europe, Asia, and other locations.

Among the various efforts on the development of the pseudo dynamic testing throughout the 1980s, most notable was the U.S.-Japan Cooperative Research Using Large-Scale Testing Facilities, sponsored jointly by the U.S. National Science Foundation and the Japanese Ministry of Construction. Prof. J. Penzien and late Prof. H. Umemura were the leaders of this research, and Prof. M. Watabe and Prof. R. D. Hanson served as coordinators. In this research, the pseudo dynamic test was applied to a full-scale seven story RC structure and a full-scale fix story steel structure, both tested at the Ultra-Large-Scale Testing Laboratory of the Building Research Institute. Those were the very first efforts to apply the pseudo dynamic test to real-scale structures represented as multiple degrees-of-freedom.
systems. In the applications, problems of erroneous, divergent responses were disclosed, and it was found that experimental errors associated with actuator-control were responsible for such behavior and the errors were aggravated with the increase of degrees of freedom. To remedy those problems, new algorithms were devised to minimize and/or dampen the erroneous responses. In line with those studies, serious discussion was also made as to the incorporation of the substructuring techniques into the pseudo dynamic testing, and new integration methods that fit to the fundamentals of the test and can ensure unconditional stability in the direct integration. All those efforts were conducted with tight communication between the U.S. and Japanese researchers involved. They met regularly in Japan, exchanged ideas and progresses, and wrote many papers on the concerned subjects. This friendly, harmonious, and collaborative atmosphere was one of the most significant assets of this research, achieved only thanks to the strong and thoughtful leadership exercised by Profs. Penzien, Umemura, Watabe, and Hanson. This research also served as an engine to disseminate the pseudo dynamic testing in the earthquake engineering communities throughout the world.

The pseudo dynamic testing is still evolving. One of the hot subjects at the present time is real-time control in pseudo dynamic testing. Here, the test object is to be loaded on a real-time scale rather than quasi-statically. A sequence of loading, control, and computation in the real-time is essential in this testing, made possible thanks to the significant progresses of recent electronic technologies. The real-time testing opens an opportunity to directly incorporate the rate-of-loading effects on structural characteristics into the pseudo dynamic testing. A summary of recent efforts on real-time testing is presented in (Philosophical 2001).

In the earthquake engineering study, a variety of experimental methods are available, such as the conventional quasi-static loading test with a predetermined loading history, shaking table test, pseudo dynamic test loaded quasi-statically, and pseudo dynamic test loaded in the real-time. Each has its own merits and drawbacks relative to others, and one should choose the best method in view of the respective research objectives. The writer’s view on the choice is presented in (Nakashima 2001).

ACI-SP84 (1985). “Earthquake effects on reinforced concrete structures, US. - Japan research,” Special Publication SP84, American Concrete Institute.
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Earthquake Engineering In Chile: From the 60’s Until Now

This presentation focuses on the strong influence that Professors Ray Clough and Joe Penzien had on the work of some of their former students, on the work of those who came later to Berkeley, who learned structural dynamics by using their outstanding textbook, and who are trying to continue developing this interesting and elusive field of engineering.

Before 1960, the discipline of structural engineering in Chile was taught by engineers who worked in the profession. Research facilities as well as investigators in the field were scarce. By that time, leading universities in the country began a new strategic plan that included sending engineers to the best universities abroad to pursue graduate studies, and once back, become full-time professors. As a result of that, new research facilities were constructed and the concept of a university campus was implemented. After the usual resistance, courses and curricula were improved significantly and publications become a normal requisite to be promoted.

Currently, our department has 12 full-time professors, most of them with graduate studies either in the USA or Europe: four with Ph.D.’s from Berkeley, three from Illinois, two from Texas-Austin, two from Europe, and one from our own doctorate program. Two former professors, no longer part of this Department, also came to Berkeley. Nowadays we have testing facilities for quasi-static and cyclic tests of structural elements up to 100 tons in shear, a 100 ton and 25 ton rig for dynamic tests of seismic isolators and energy dissipators, a 6-degree of freedom dynamic simulator, and two universal testing rigs for elastomeric compounds. In addition, dynamics tests of soils and rocks are performed in our Geotechnical laboratory.
The studies performed in our group, both analytical and experimental, have influenced code design provisions over the past 20 years. The history of seismic codes in Chile is marked by the occurrence of severe earthquakes. Indeed, in May 1960, the Seismic Code Committee had a draft ready to be issued as the first code for Earthquake Resistant Design of Buildings. As you know, a destructive 8.5 magnitude earthquake struck the southern part of the country, and the draft had to be re-studied to incorporate the seismicity of that part of Chile. Twelve years passed before the code was approved and became an official document. A revised version of this code was initiated as a consequence of the March 3, 1985 earthquake that struck the central part of Chile, and also prompted by the damage experienced by social housing erected with the approval of governmental agencies. This new version was published in 1993 and was modified in 1996. More recently, a seismic code for the design of industrial structures and facilities has been developed and it will become an official document by the end of this year. The next step is a code for the analysis and design of seismically isolated buildings, which draft is already available and will begin to be discussed shortly within the corresponding committee.

The most significant feature of building construction in Chile has been the extensive use of shear walls, both in reinforced concrete and masonry. This practice has yielded structural systems with significant lateral overstrength, limiting the development of large ductilities and, hence, structural damage under severe earthquake motions. Industrial facilities, where steel construction is widely used, also showed a satisfactory seismic behavior during the 1960 and 1985 events. This behavior during previous earthquakes has influenced the seismic design provisions included in our building codes.

Seismically-isolated buildings have also begun to be constructed in Chile. The first case was a prototype 4-story social housing building constructed in 1993, under the supervision of the structural group of the Universidad de Chile. Later in 1996, our group began a 3-year project in conjunction with the government to promote the use of innovative systems for vibration reduction. As a result of this project, the first base-isolated hospital with 52 high damping elastomeric bearings was constructed in Chile. Then came the new building of the Engineering Faculty of our University with 11 frictional sliders and 43 elastomeric bearings, which is about to be finished. The next step is the Military Hospital, designed by one of our former students, with 164 elastomeric isolators and to be constructed between 1992 and 1994. Several bridges have been designed also with seismic isolation and energy dissipation devices, and the technique is becoming popular in the country.

There is no doubt that our education at Berkeley in the 60’s, 70’s, and 90’s has shaped our research in Earthquake Engineering. Our “relative” success is attributed to the excellence in the education we received from its faculty, from our advisors. Their knowledge has gone beyond the frontiers of countries and has helped thousands of professionals all around the world to mitigate the damaging effects of earthquakes.

Today, we face new challenges that will need greater creativity and innovation from all of us involved in the field. It is not a mystery that funding for research in this field is becoming harder every day. Moreover, finding top students interested in the field is also not as simple as before. It would be easy to blame that on the new evolving technologies; however, it should be recognized that our profession has not been keeping pace with the new technologies. New knowledge takes too long to get into practice, there is resistance to incorporate innovation as if we were afraid of the end of our discipline. We should look for that last day since that will be the day we succeed, not before.
Session 6: Structural Design and Retrofit
Contributions of Professors Clough and Penzien to Current Trends in Structural Design and Retrofit

In these introductory remarks the chairman would like to first acknowledge that he has had the privilege of knowing and working with Professors Clough and Penzien since 1958, and that their devotion to teaching and research and their excellent publications and professional activities have had a significant influence on his teaching, research and professional activities. The main purpose of these introductory remarks is to point out the significant contributions that Professors Clough and Penzien have made to what the chairman considers to be the current trends in structural design and retrofit of civil engineering facilities when they can be subjected to significant earthquake ground motions (EQGMs). Thus, the chairman will attempt to present first, his personal opinions regarding what are these trends and then what are the needs for introducing these trends in simple but reliable code provisions.

The economic losses induced by the 1989 magnitude (M) 7.1 Loma Prieta EQ were considered as unacceptable by the earthquake engineering (EQ E) community and it recognized the need for developing new code provisions based explicitly on specific performance objectives for the different levels of seismic hazards (EQGMs). This recognition triggered what the chairman considers the beginning of the current trends in structural design and retrofit of civil engineering facilities. Groups of practitioners and researchers started to discuss what can be done to develop a performance based seismic resistive code. In January 1994, the M 6.7 Northridge EQ occurred resulting in economic losses significantly more severe than those that resulted from the Loma Prieta EQ. This increased the pressure for the need to develop recommendations and/or guidelines for performance based design and construction procedures for new facilities as well as for the assessment of the seismic vulnerability of existing facilities and their seismic upgrade. This resulted in the development of the three following documents: (1) “Performance Based Seismic Engineering of Buildings” (1995 report by the SEAOC Vision 2000 Committee); (2) “Methodology for Evaluation and Upgrade of Reinforced Concrete Buildings” (1996 Report No. ATC-40); and (3) “NEHRP Guidelines for Seismic Rehabilitation of Buildings” (1997 Report No. FEMA-273).
Although in general the above documents have been well received by the earthquake engineering community, still there are engineers (practitioners as well as researchers) that have expressed their concern about the practical application of the recommended and/or proposed guidelines. While some of them claim that there is nothing new in these guidelines there are others, particularly the practitioners, that are concerned that by implementing performance-based seismic design in practice they might result in a significant increase in their professional liabilities. Therefore it is not surprising that the recommended guidelines have not yet been incorporated in the current building codes.

After presenting the definition of Performance-Based Engineering (P-B E), Performance-Based Seismic Engineering (P-B SE), and Performance-Based Seismic Design (P-B SD) and discussing briefly the conceptual framework for P-B SE and the Performance Based Seismic Design Objective Matrix (P-B SDOM) attempts are made to: First, answer the following question, “Are there any new concepts in the conceptual framework for P-B E and in the P-B SDOM”?; and then to identify the main issues involved in the development of reliable P-B SE code provisions.

Regarding the above question different answers can be obtained depending on how the definition of P-B SE is looked upon or interpreted.

Regarding the identification and definition of main issues involved in the development of reliable P-B SE code provisions, several attempts have been already made not only to identify key issues but also to develop action plans that could be used to develop P-B SD criteria. After presenting a list of the technical issues involved with just P-B SD as well as a list of the key issues involved in the development and implementation of the general engineering procedures that should be considered in P-B E code provisions, the importance of each of these key issues is discussed briefly. A comparison is made of these lists with the lists of Professors Clough’s and Penzioni’s achievements, in the area of seismic structural design and retrofit, that they have attained through their professional activities, teaching, research and publications. This comparison reveals that they have made very significant contributions not only to the betterment of the current seismic design and retrofit practices, but also in providing important information regarding what at present are considered to be the key issues that have to be considered for the development of simple but reliable seismic code provisions for the implementation of the proposed P-B SE philosophy.
Wind Load Design of Tall Buildings

The lateral stiffness of a tall building can be provided by the interaction of core and shear walls and frame tubes which should be properly distributed such that the building will deflect mainly in the direction of the applied force without inducing significant response in other directions and twist. Core and shear walls contribute to flexural and torsional rigidities which are essential in the lower quarter of the building while a closed periphery frame tube comprising deep spandrel beams and flat columns provides effective resistance to lateral loads in the upper three-quarters of the building. The design and performance of a tall building in terms of peak drift and maximum acceleration under wind load are discussed.

Conceptual Design of Structural System

In many tall buildings, especially where the plan and configuration are irregular, the core wall is placed eccentrically due to architectural requirements. An example is the 70-story reinforced concrete building constructed in Bangkok of which the perspective and typical floor plans are shown in Figs. 1-6. In this building, the core wall housing the lift, vertical service shafts and staircases are located eccentrically to the left of the building. To alleviate the adverse effect of this eccentricity and to improve the torsional rigidity, two shear walls of 1.5m thick and a shear wall of 1.0m thick are introduced from grid points A-1 to A-5, R-1 to Q-5 and A-19 to F-21 respectively as shown in Fig. 2. The 1m thick shear wall is terminated at the first floor level at the main entrance but the two 1.5m walls are present up to the 13th floor. A line of braced frames (Fig. 7) is provided along grid line 19 between grid lines C and G from the basement B6 to 1st floor and 5th to 13th floors as shown in Figs. 2 and 4 respectively. This is supplemented by three other braced frames at grid lines 11, 13 and 15 between grid lines A and C from 1st to 5th floors (Fig. 3) to provide the continuity of the transfer of lateral load at these levels.

Finally, two smaller frame tubes are placed on the two adjacent sides of the main tube as indicated in Fig. 5, to cater for the eccentricity in the upper portion of the building. One of these smaller frame tubes gradually disappears above the 46th floor (Figs. 5-6). In this building the periphery frame tube consists of deep spandrel beams and flat columns (Fig. 8). Greater depth can be allowed for the spandrel beams between the windows and/or doors in consecutive floors without increasing floor to floor height. The shear and torsional rigidities can be further enhanced through the closer spacing of the periphery columns in the upper three quarters of the building.

Structural Response To Wind Load

The mean wind velocity profile is defined by $U(z) = U_0(z/z_0)^{m}$ where $z_0 = 300$ m, $U_0 = 42.3$ m/s. The frame tubes in the upper portion of the building reduce greatly the peak displacement due to twisting from 64 mm to 27 mm based...
on damping factors of 0.02. The value decreases further to about 12 mm with the presence of shear walls at the lower level which also reduce substantially the along-wind peak displacement from 189 mm to 131 mm. The cross-wind peak displacement of 137.5 mm and the maximum acceleration of 13.44 milli-g are within acceptable ranges of values in common practice.
A research project entitled “An Investigation of the Effectiveness of Existing Bridge Design Methodology in Providing Adequate Structural Resistance to Seismic Disturbances” sponsored by the U.S. Department of Transportation, Federal Highway Administration was initiated after the 1971 San Fernando Earthquake at the Earthquake Engineering Research Center, University of California, Berkeley. Professors Joseph Penzien, Ray W. Clough and William Godden supervised the investigation and Prof. J. Penzien served as Principal Investigator.

The investigation consisted of five Phases. In the 1st Phase, a detailed literature survey on the seismic performance of bridges was conducted by Dr. Toshio Iwasaki and Profs. J. Penzien and R.W. Clough. Dr. Wen-Shou Tseng and Prof. J. Penzien developed a sophisticated analytical model of long, multi-span bridges in Phase 2. This included an analytical model of expansion joints that takes account of the effect of pounding and restrainers. A special feature of the model was the “impact spring” that was used to simulate the pounding effect between two bridge decks. They used the model to analyze the 5/14 South Connector Overcrossing that collapsed in the 1971 San Fernando Earthquake. Since it was a curved bridge with multi-internal hinges, the effect of pounding and restrainers was very important to its seismic performance. Dr. David Williams and Prof. W. G. Godden conducted a shake table test for the 5/14 South Connector Overcrossing in Phase 3. They found a significant pounding effect at the internal hinges. Dr. Ma-Chi Chen and Prof. J. Penzien conducted an analytical investigation on the seismic response of short, single and multi-span bridges in Phase 4.

The author stayed at the EERC from April 1975 to July 1976 under the supervision of Prof. J. Penzien to participate in Phase 5, “Correlative Investigation on Theoretical and Experimental Dynamic Behavior of a Model Bridge Structure.” The purpose of Phase 5 was to correlate the experimental bridge response in Phase 3 with the analytical model developed in Phase 2. The analytical model for the impact spring developed in Phase 2 was modified so that it simulates the elastic pounding. The correlative study was successfully completed.

It was the first time for the author to be involved in research on the effect of pounding and restrainers between bridge decks. The series of investigations was an important landmark for research on the seismic response and performance of urban freeway viaducts under strong seismic disturbance. It stimulated the seismic researches and affected the seismic design and retrofit of bridges worldwide.
Restrainers, or unseating prevention devices in a broader sense, were first developed and implemented in bridges after the 1964 Niigata, Japan, Earthquake. Extensive damage of bridges that resulted from excessive relative displacements between superstructures and substructures created an inspiration for developing unseating prevention devices. They include steel plate connectors, bar connectors, cable restrainers and chains that tie two decks or a deck and a substructure. Providing sufficient seat length is an important unseating-prevention measure. Today unseating prevention devices have become an important component of bridges worldwide.

However, because unseating prevention devices are not expensive structural components, little attention has been given to develop a comprehensive design procedure after the pioneering research at EERC. The seismic design force has been crudely obtained by multiplying a static seismic coefficient by a reaction force. Effect of pounding has also been considered a secondary importance in seismic design, since pounding results in only local damage at the end of superstructures.

Because of the widespread damage, which occurred in the recent earthquakes in the USA, Japan, Taiwan and Turkey, the importance of unseating prevention devices and pounding effects on the total response of a bridge system is becoming widely accepted. Although pounding causes only local damage at the contact face, it transfers large seismic lateral forces from one deck to another, which results in a significant change in the seismic response of the entire bridge system. Unseating prevention devices also affect the total response of a bridge system. A good example for this is the collapse of an approach span of the Nishinomiya Bridge system, Hanshin Expressway in the 1995 Kobe, Japan, Earthquake. The main bridge, Nishinomiya Bridge, was a Nielsen Lohse bridge with a mass of 12,000 t, while the approach span was a steel plate girder bridge with a mass of 1,900 t. These two structures were tied together by plate-type restrainers. The damage was initiated by failure of fixed-bearings of the main bridge. This allowed large response displacement of the main bridge to take place, and the main bridge pulled the approach span, which resulted in failure of the fixed-bearings in the approach span. As a consequence the approach span dislodged from its support when the decks moved in the other direction. The unseating prevention devices were not strong enough to support the approach span once it dislodged from the support.

Skewed bridges exhibit a unique structural response under strong excitation either when pounding occurs between decks or when unseating prevention devices restrain deck response. Because there is a horizontal eccentricity between a line of action created by pounding and unseating prevention devices, and the mass center, the decks twist as well as the laterally displaced during an earthquake. If the skew angle is larger than a certain value, the rotation results in collapse of a skewed bridge without contact of the deck ends with its abutments or adjacent decks.

Extensive analyses and experiments are being conducted on the effect of unseating prevention devices and pounding effects. Based on experiments and analyses, it is now known that tying together two adjacent spans is not appropriate if the masses or natural periods of the two spans are very much different, as was the case of the Nishinomiya Bridge. In such an instance, enough seat length should be provided for the prevention of the spans from dislodging from their supports. Various new devices are continuously developed for unseating prevention devices.
Evaluation and Repair of Earthquake Damaged Buildings

In 1999 the Applied Technology Council completed a project (ATC 43 - Technical direction by Craig D. Comartin) funded by the Federal Emergency Management Agency (FEMA) addressing the evaluation and repair of earthquake damaged wall buildings. These building types included reinforced concrete walls, reinforced masonry walls, unreinforced masonry walls, and frames with infilled masonry walls. The results are presented in three documents. 

FEMA 306: The Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings - Basic Procedures Manual documents performance based evaluation procedures. The procedures address the investigation, documentation, and classification of damage caused by earthquakes to building components according to mode of structural behavior and severity. This information is used to evaluate the effects of the damage on the performance of the building during future earthquakes. FEMA 307: The Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings - Technical Resources provides supplemental data that facilitates application of the procedures and includes an example application. FEMA 308: Repair of Earthquake Damaged Concrete and Masonry Wall Buildings addresses the use of a performance based methodology to select appropriate action to accept the damage as is, restore, or upgrade the earthquake damaged building.

The procedures of FEMA 306 utilize an evaluation of the global performance of the structure given the evaluation of damage of its individual elements. A unique feature is the component guides to assist in the evaluation of the significance of observed damage to building elements. The procedures of FEMA 308 result in a policy framework that is capable of incorporating improved decision alternatives for damaged buildings. The three alternatives considered are: (1) Accept the building for continued use in its damaged condition. (2) Restore the building to its pre-event condition. (3) Upgrade the building for improved seismic performance.

This presentation will illustrate the evaluation and repair methodology and the policy framework with a two-story reinforced concrete shear wall building damaged by the Northridge Earthquake. Shear wall coupling beams that fail in pre-emptive diagonal tension are the weak links. They control the deformation capacity of the building.
This performance-based approach utilizes structural analysis procedures that focus on inelastic displacements of the building. Nonlinear static procedures (NSP) are used to generate a capacity curve relating roof level displacement to the base shear force. The maximum roof displacement that would occur during a performance level earthquake represents the expected maximum demand displacement and the displacement capacity of given structure occurs when the damage reaches the structural damage limit state for the building. For example, the Collapse Prevention displacement capacity limit of a building might be the roof displacement at which the associated damage would result in collapse of one or more of the column components.

The appropriate decision to accept, restore, or upgrade an earthquake damaged building depends on a number of interrelated factors including: the relative severity of damaging ground motion, the performance characteristics of the building after the damaging earthquake, the performance characteristics of the building before the damaging earthquake, the change in performance characteristics of the building caused by the damaging earthquake, and nonseismic issues related to the condition and use of the building.

The performance base methodology for the evaluation and repair of earthquake-damaged buildings provides the opportunity to use limited financial resources wisely. While the loss and performance values can be calculated for a specific building using the procedures described herein, the criteria for decisions to repair and/or upgrade damaged buildings have not been established. Communities need to prepare for a future earthquake by defining these parameters in a realistic manner. Selection of inappropriately high loss and low performance limits can result in too many post-earthquake potentially hazardous buildings, while selection of too onerous upgrading requirements can stall or destroy the local economy.

This abstract is based on a 12WCEE paper by Hanson and Comartin entitled *The Repair of Earthquake Damaged Buildings.*
A key to post-earthquake reliability for the transportation network is to develop improved Seismic Performance Criteria, Design Specifications and Construction Details. Caltrans has developed these features progressively as lessons were learned from the 1971 San Fernando Earthquake and subsequent seismic events. The development was supported by an unprecedented research program that has provided the bridge design community the assurance that the new specifications and improved seismic details will result in bridges that 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 June, 1990 Governor’s Board of Inquiry report, “Competing Against Time.” The twelve year old Seismic Advisory Board (SAB) 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. Dr. Joseph Penzien has been a member of that SAB since 1990 and has been the chairman since 1995. In many instances the Advisory Board has positively influenced Caltrans Upper 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. Examples of good performance of new seismic design details during recent earthquakes are presented to validate the philosophy and implementation procedures.

The major elements of a strong seismic design program include the development and adoption of a Seismic Performance Criteria. What performance is expected of a bridge and what level of earthquake should govern the design? Second, extensive research and proof testing of proposed details is necessary to insure that the bridge will perform as the designer expects. A part of this element is the installation of various strong motion instruments to record the accelerations during subsequent earthquakes, and to analyze the response of the bridges. Third, it is very important to have emergency planning completed ahead of time so that important lifeline routes are identified, detours are ready for use, rapid response to damage cleanup will occur, and reconstruction will be implemented on an accelerated schedule.

Caltrans’ seismic design philosophy is based on creating structural resilience. This is accomplished through structural continuity, minimizing joints and bearings, both of which are major maintenance problems. A second element in accomplishing that philosophy is the use of ductile design details, where displacement criteria govern over strength in most cases. This results in predictable and controlled damage during an earthquake. Demand-capacity analysis of major structural members is a key step in successful seismic bridge design. The foundation-structure interaction is also now considered in the global model.
The design begins with a site-specific peak rock acceleration based on the CDMG Map 45 and the proximity of a structure to the nearest fault. Acceleration response spectra have been developed to bring the rock accelerations up through the soil above the bedrock. The acceleration response spectra have been developed for various depths of material for both hard soil and alluvium and for deep soft mud. For major and complex structures site-specific response spectra must be developed.

A major “problem focused” research program was funded to develop and proof test the various design details which have been utilized for both new bridges and retrofit strengthening of older, non-ductile bridges. The University of California system provided a major share of this research support at five campuses. Over $55 million has been expended to date and a guaranteed $5 million annually has been institutionalized in the Caltrans budget. The Northridge Earthquake of 1994 provided a real time test of many of these details in a high moderate seismic event.
Session 7:
Special Structures
An Overview of Special Structures

We have seen a tremendous change in the state of knowledge of structural engineering and structural mechanics during the half-century of 1950 to 2000. This period coincides with the span of time when Professors Ray Clough and Joseph Penzien were active in these fields. Their names appear frequently with other leaders of the profession when new knowledge in methods of analysis or a novel design approach is presented. Their contribution has been direct when they were participants in the project team and indirect when other engineers were utilizing the methods that were developed by them.

When we trace back the work done by Professors Clough and Penzien their students and colleagues will point invariably to the textbook *Dynamics of Structures* or to their many reports and papers on earthquake resistant structural design and analysis. They will also note that Clough with his work in Finite Elements and Penzien in his work with Reliability and Probabilistic Methods have given the profession a leap forward in analysis for safe design. In fact the Citations by the National Academy of Engineering read for Clough: Election to the Academy for “analyses, design and applications of structures for dynamic loadings, including earthquakes,” and for Penzien: Election to the Academy for “probabilistic methods in earthquake engineering with emphasis on linear and non-linear structural response analyses”

As a person who has been active in the field of structural engineering and structural mechanics during the same period when Clough and Penzien were doing their research and teaching their courses at the University of California at Berkeley, I recall that when Clough joined the faculty, there were no courses offered in dynamics or earthquake engineering in the Civil Engineering Department. In fact, graduate students were asked to take a course in mechanical vibrations in the Mechanical Engineering department that made no reference to structures. Dynamics of structures became part of the curriculum thanks to Clough’s presence in the department, and earthquake engineering reached its place of prominence thanks to Penzien’s leadership as Director of the Earthquake Engineering Research Center. Other speakers in this Symposium will talk about their achievements in greater detail.

This session of the symposium covers the area of “special structures”. The word “special” implies that these structures are different than ordinary structures. Buildings, bridges, highways, manufacturing facilities, power plants are ordinary structures. They become special if they are exposed to unusual forces, or their geometric configuration is unique, or they house and protect systems for which there are special design requirements.
We can cite the following as examples:

- Buildings whose three-dimensional geometric configurations require very sophisticated methods of structural analysis. An example is the Disney Concert Hall in Los Angeles.

- Offshore structures that are subjected to hydrodynamic forces and wave action. An example is the 470 meter tall concrete offshore platform, Troll A, located off Norway.

- Structures that are designed to adapt to the movements of the soil below the foundations or to other external loads of unconventional origin. An example is the 1.7-kilometer long Kansai International Airport terminal structure on an artificial island in Osaka Bay.

- Very massive structures that have special design problems for their sheer size and configuration. An example is the concrete gravity Three Gorges Dam under construction on the Yangtse River.

- Bridges that are exposed to aerodynamic forces or to vertical loads that cause lateral vibrations. An example is the cable stayed Millennium Bridge crossing the Thames River.

- Structures designed to resist nuclear weapons effects, a field of structural engineering that was very important in the first three decades of this half-century. Examples of such structures are underground reinforced concrete military command centers.

Speakers in this session have chosen their own topics and we are pleased that they will make their presentations on “Special Structures” having in mind the contributions of Ray Clough and Joseph Penzien.
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**HASSI and SSI Analysis of Heavy Structures**

**Introduction**

For mitigating undue risks caused by strong earthquakes to such important structures as reactor buildings and high arch dams, we need a clear rationale of Soil Structure Interaction (SSI), and a practical analysis tool in the form of computer codes with reasonable consideration of relevant data. At the same time, SSI analysis should be performed in three-dimensions as reasonably and practically as possible.

In pursuing this objective, we developed the HASSI (Hybrid Analysis code for Soil Structure Interaction) series of computer codes with Dr. Joseph Penzien, which consider non-linear effect to the foundation media surrounding a structure and the modification of earthquake input motions to the structure. The HASSI series codes were verified using forced vibration tests and simulation of observed motions of small-scale models constructed for the verification study by us in Japan.

HASSI-6 to HASSI-8 were used for the blind tests of a series of observed response records of large-scale models of reactor buildings at the Lotung and Hualian sites in Taiwan. Our experience and technical capability acquired through the above studies have been applied to the simulation of the recorded responses of the Nagawado high arch dam in the 1984 Nagano-ken Seibu Earthquake of M 6.8.

**Contribution of HASSI to the Interpretation of Three-Dimensional Response of Reactor Building Models**

The foundation media surrounding such heavy structures as nuclear reactor buildings would behave as a non-linear transmitter of input earthquake energy to the structures. HASSI series codes which consider the strain-dependent non-linearity of surrounding soils by the equivalent linearization method were verified using forced vibration tests and response motions obtained at our small-scale models of PWR reactor buildings built at Kazusaminato site in Japan. HASSI-7 and 8 refined with substructuring algorithms were used for the blind simulation studies of large scale models at the Lotung and Hualian sites in Taiwan and provided remarkably good results. 
Contribution to the Interpretation of Three-Dimensional Response of Nagawado Arch Dam

The importance of including the far-field impedance along the dam-foundation boundary along with the upstream reservoir water in the dynamic analysis of an arch dam was confirmed in the simulation of the recorded responses of the Nagawado Arch Dam. The results of the simulation study were submitted, thanks to the invitation of Prof. R. W. Clough, to the US-China Workshop on Earthquake Behavior of Arch Dams held in China in 1987\(^2\). The recorded responses were analyzed and published by EERI, independently\(^3\).

Through the above studies, we obtained some important results as follows:

1) The dominantly remarkable responses were those of the 1st antisymmetric arch mode and 2nd cantilever mode of vibration observed at the crest arch with the lowest frequency ranging from 2.0 to 4.4 Hz with the estimated total damping less than 4.73% including the material damping of 2%.

2) When the impedance function along the dam-foundation interface was replaced by a limited volume of foundation rock elements with fixed boundary, the outgoing waves from the interface to the foundation media were reflected back at the boundary and generated non-real large repetitive response motions of the dam.

3) Upstream water reservoir acts to suppress the radial response of the dam.

Concluding Remarks

We would like to express heartfelt thanks to Dr. Joseph Penzien for his precious and sincere advisory activity over our fellow engineers since 1982.

References


The Contributions of Joseph Penzien and Ray Clough to Bridge Design Methodology following the San Fernando Earthquake

This presentation will focus on some of the contributions by Professors Joe Penzien and Ray Clough to seismic bridge design practice, as we know it today. They recognized the need for increased understanding of bridge response to the effects of earthquakes following the San Fernando earthquake in 1971. Penzien and Clough responded with a research project entitled “An Investigation of the Effectiveness of Existing Bridge Design Methodology in Providing Adequate Structural Resistance to Seismic Disturbances.” This project was funded by the U.S. Department of Transportation, Federal Highway Administration (FHWA). It was one of the first research projects to specifically focus on seismic design of bridges. The project was composed of six phases, which included:

1. Conducting a worldwide literature survey of seismic design provisions for bridges.
2. Development of nonlinear dynamic response analysis techniques for bridges and follow up analytical investigations of the damage suffered to multiple-span highway overcrossings in the San Fernando earthquake.
3. Conducting analytical investigations on the dynamic response of short and single span bridges using newly developed computer algorithms for this type of bridge.
4. Performing detailed model experiments on the shaking table to provide dynamic response behavior similar to prototype behavior of bridges that failed in the earthquake.
5. Conducting correlation studies using the newly developed computer algorithms with results obtained on the shake table.
6. Preparation of recommendations for the bridge seismic design specifications.

The last phase of the project concludes with several recommendations that are in the current AASHTO seismic design specifications. These recommendations were made in concert with the developments that were on-going at Caltrans. The seismic design specifications were adopted by AASHTO and became the first modern day seismic design provisions for national use. Subsequent to the AASHTO adoption of the Caltrans specifications, a second project was initiated by FHWA (i.e. Applied Technology Council – 6) to develop a seismic bridge design for national use. Their contributions from the initial research also had an impact on the development of the ATC-6 seismic design guidelines.

This presentation attempts to recognize their contributions and the impact that they have had on the bridge engineering profession. Several examples are given to demonstrate their ability to reach out beyond academia and provide practical solutions to bridge engineering.
A concrete arch dam impounding a large reservoir presents a major potential hazard to downstream centers of population, especially if the dam is located in an active seismic region. Even though there is no record that a major arch dam ever has failed as the result of an earthquake, it is essential to develop and verify procedures for calculating the earthquake performance of proposed designs or existing dams. Professor Clough’s lifetime research and practice related to dams have been devoted to pursuit of this goal. The author has had the privilege of working closely with Professor Clough for more than two decades and witnesses his exceptional contributions in the development, verification, and application of analysis procedures to design and evaluation of new and existing arch dams. The impact of Professor Clough’s pioneering insights in these areas continues to grow as the application of nonlinear response behavior and consideration of rigorous dam-water and dam-foundation interaction mature. His arch dam analysis program is a testimony to the importance of two features of an arch dam that he was among the first to recognize and consider in the earthquake response analysis of arch dams. First, such a massive structure imposes significant deformations on its foundation even though an arch dam will be built only on a stiff, strong rock base. These deformations are important even under static load, but they have a much greater influence on the dynamic response during an earthquake. The second complicating feature that led to his finite-element development of one of the earliest water interaction model for concrete dams is the water impounded in the reservoir. Under static conditions this merely subjects the dam to an easily determined load, but during an earthquake the interaction with water influences both the frequency characteristics and the intensity of the resulting response. These pioneering works has led to most recent research that suggests the compressibility effects of water should be considered as well as its mass, and that inertia and damping effects of the foundation rock should also be included in addition to its flexibility.

Recognizing that verification of analytical procedures is essential to reliable earthquake performance evaluation of dams, in 1981 Professor Clough initiated a US-China cooperative research program funded by the National Science Foundation that led to field measurements of five arch dams in the past two decades. The purpose of this cooperative research was to conduct field measurements to study the dynamic interaction between arch dams and their foundation and reservoir water. The experimental procedure was to excite the natural vibrations of selected arch dams using rotating mass shakers, and to measure the resulting hydrodynamic pressures and dam and foundation responses that could then be used for verification of analytical procedures of the dam-water-foundation system. Two arch dams in China were studied in this way with Professor R.W. Clough of the University of California and Vice President K.T. Zhang of Tsinghua University as the principal Investigators: Xiang Dian Hong (XHD), a gravity arch dam with cylindrically curved upstream face, and Quan Shui (QS), a doubly curved thin shell dam. Results of these studies
were used to validate representative foundation rock and water interaction models for practical applications. These tests were followed by another test at Monticello Dam in California concentrating exclusively on the hydrodynamic interaction mechanism, with Professor Clough acting as the principal investigator and the Chinese delegates attending as observers, while the author participated as consultant to project as he had done in the two previous studies. Results of the study at Monticello Dam showed that hydrodynamic pressures measured on the face of the dam were in reasonable order-of-magnitude agreement with calculated results. Consideration of compressibility made little difference in the comparison, mainly because vibration frequencies of the dam and the reservoir water differed enough that interaction effects was not great.

The most recent phase of the US-China cooperative research on “Dynamic Interaction Effects on Arch Dams,” began in 1991 with study of two tallest arch dams in China. These recent studies were conducted with Dr. Y. Ghanaat and Professor H.-Q. Chen assuming responsibility as principal investigators, while professors Clough and Zhang participating as Project Advisors. The objectives of these latest research were to develop new testing procedures for exciting the entire dam-water-foundation system, to obtain improved data on the dam-water and dam-foundation interaction effects that would enable better validation of the existing analytical procedures, and to develop procedures for measuring the reflection coefficient of the lake-bottom materials. The first test series were conducted at the 157-m high Dongjiang Dam where the dynamic response of the dam and its retained lake was excited by detonating explosive charges in boreholes drilled into the solid foundation rock at a distance of 800 m downstream of the dam; these were intended to excite the dam-water interaction by blast-generated waves traveling through the foundation rock. In addition, two approaches based on seismic refraction and seismic reflection techniques respectively were developed and used for the first time to measure the reflection coefficient of the lake-bottom materials. The second test series were performed at Longyangxia Dam, a 178-m high concrete gravity arch structure, except that the dam and its retained lake were excited by detonating large explosive charges in shallow water about 1.2 km upstream from the dam. During this experiment a new procedure based on the acoustic reverberation concept was explored to measure an overall average value for the wave reflection coefficient of the reservoir boundary materials.

These experiments have demonstrated that the dynamic response of concrete arch dams and their retained lakes can be excited successfully by detonating explosives in boreholes or in water. The recorded dam responses and hydrodynamic pressures were more than an order of magnitude larger than those measured in previous tests using rotating mass shakers and have provided clear evidence of water compressibility effects on the response of Dongjiang and Longyangxia Dams. The acoustic reverberation tests showed that the wave reflection coefficient appears to be frequency dependent. The recorded signals along the dam-rock interface indicated that the magnitudes and phasing of motions vary at different locations and are affected by the dam-foundation interaction as well as the canyon topography. In summary these experiments have produced probably the most complete sets of data now available for study of dam-water-foundation interaction effects, and correlation studies have produced results that characterize the sensitivity of the dam response to various modeling assumptions.
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**Earthquake Behavior of Arch Dams**

A joint “US-China Workshop on Earthquake Behavior of Arch Dams” was held in June 1987 at the Qinghua University in Beijing, China. The workshop was co-chaired by Professor Ray W. Clough and Professor Zhang Guangdou. At the end of the Workshop, they presented closing findings and comments, which listed urgent research needs on earthquake behavior of arch dams. The needs included seismic input, foundation-dam interaction, reservoir-dam interaction, nonlinear dam response, field observations, concrete material tests, abutment stability, earthquake resistant measures and simplified analysis procedures. This presentation discusses one of the most significant advances in the field of earthquake and arch dams, nonlinear dam response, since the Beijing Workshop fifteen years ago.

With the advance in the finite element analysis, it is a simple matter to make a full dynamic time-history analysis of arch dam under seismic loading. However, it is difficult to explain/interpret the high tensile stresses predicated by a linear elastic analysis. From the middle 1970s to the middle of 1980s, studies were made to evaluate the tensile strength of mass concrete, notably work by the Bureau of Reclamation and by the late Professor J. M. Raphael. These studies indicated that mass concrete does have substantial tensile strength, particularly under dynamic loading such as earthquake.

At the same time, it became obvious that the linear elastic analysis does not represent the true behavior of arch dams under strong earthquake loading. Not only is the behavior nonlinear, most arch dams are not even continuous structures. Arch dams are constructed in blocks separated by vertical contraction joints. The joints can transmit compression but have very little tensile strength. Arch dams are designed to transmit water loads to the abutments by compression. The lack of tensile strength in the contraction joints does not affect the load carrying mechanism under static loading. When subject to oscillatory seismic loading, large tensile stresses, particularly in the arch direction, are unavoidable using linear elastic analysis.
As arch tensile stresses develop under earthquake loading, vertical contraction joints will open momentarily to release the stresses without causing cracks in the dam. After loading the earthquake, contraction joints will be back in compression again under static water load. This theory was raised first by Professor Clough. Researches have been performed since the late 1980s to investigate this joint opening mechanism. Analytical work has been performed by Professor G. L. Fenves at Berkeley and by Professor J. F. Hall at Caltech. They developed software to perform nonlinear dynamic analysis of arch dams considering joint openings. At the same time, experimental work has been performed by Professor Chen Houqun using the 5m x 5m shaking table at the Institute of Water Conservancy and Hydroelectric Power Research in Beijing. Other researches have been performed in Europe.

One of the most significant advances on this subject to date is the successful duplication of experimental results analytically. The experimental work was made by Professor Chen on a 1/300 scaled model of the 250m high Laxiwa Arch Dam on the Yellow River in China. Tests were performed first on a monolith model. Then three vertical joints were cut on the same model and the tests repeated. Test results showed that indeed vertical joints opened to release arch tensile stresses during earthquake. Test results also showed that cantilever stresses increased as the arch tensions decreased due to joint openings. Subsequent analyses, using software developed by Professor Fenves, reproduced the experimental results. Details of these studies have been published at the Fourth International Benchmark Workshop on Numerical Analysis of Dams, in Madrid Spain, September 1996. (“Joint Opening of Arch Dam During Earthquake, Experimental and Analytical Results” by H. Q. Chen and C. H. Yeh)

The above is an important step toward better understanding of the earthquake behavior of arch dams. More work will be required to address the rest of the questions listed in the first paragraph.
Cordial Friendship and Successful Cooperation  
in honor of professor Ray W. Clough

In recognition of Professor Clough’s distinguished achievements and contribution in the areas of earthquake engineering research and education, especially in cooperative research efforts in China, he has been elected as a foreign member of the Chinese Academy of Engineering during the third general assembly of the CAE in June 1996. Previously, he has been conferred the title of Honorary Fellow of the China Institute of Water Resources and Hydro-power Research.

Professor Clough began his cooperative activities with Chinese colleagues in earthquake engineering as early as 1974 when he visited China as a member of the U.S. Earthquake Prediction Delegation. After than he has made great efforts to visit China many times for the China-US cooperation.

Since 1978 some Chinese researchers luckily worked with Professor Clough at U.C. Berkeley working on dam engineering. They have played an important role afterward in areas of earthquake engineering of dams in China.

In 1980 Professor Clough gave a lecture series on Finite Elements and earthquake engineering to an advanced group of civil engineering students and engineers at Tsinghua University. The lectures evoked excellent responses from all participants.

In 1981 the Dynamics of Structures, co-authored by Professors Clough and Penzien, has been translated into Chinese. In China this book became a popular textbook for college and university postgraduate students as well as the basic reference book for practicing engineers not only in the field of civil engineering but also in many other engineering fields in which structures are subjected to dynamic loads.

More significant contributions made by Professor Clough to the China-U.S. Cooperative research are the long-term bilateral cooperation in earthquake studies on large arch dams during the past twenty years. The extensive research effort includes the completion of five successful field measurements on arch dams with joint financial support from U.S. and China under the China-U.S. Protocol for Scientific and Technical Cooperation in Earthquake studies. The cooperative research program has successfully achieved its expected ultimate purposes. There is no question that the results of these cooperative studies were much more than could have been obtained by any single one of the participating institutes.
During the course of implementation of the cooperative research program, Professor Clough together with the Chinese partners organized a successful workshop on arch dams in China in 1986 with participation of 50 national experts from all over the work. In 1982 and 1983 Professor Clough visited the Er-Tan dam site and had extensive discussions with the dam design team concerning the dynamic earthquake response analysis of the dam.

All the mentioned outstanding contributions of Professor Clough’s cooperative research efforts in China bring us not only the technical benefit, but also the people’s friendship from U.S. That is why Professor Clough enjoys high prestige in civil engineering circles in China.
Session 8:
Emerging Technologies
Recent Research in Sensors and Smart Structures Technology

NSF has established a new research program to capstone the transformation of civil infrastructure practices from conventional engineering methods to technology-based approaches. This program focuses on advanced sensors technology, which is the essential element to enhance system intelligence. This paper describes the short-term and long-term research goals, the diversity in disciplinary dependence, and its broad-based applications, including enabling of intelligent infrastructure systems, structural health monitoring, natural hazard mitigation, and advancement of autoadaptive media.

Recent major events for program development, such as international workshops to advance cross-agency interests in future sensing systems, including sensor informatics and sensor intelligence, and forums to establish solid partnerships with industry will also be introduced.
In 1999, the National Science Foundation launched a major new research initiative known as the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). This 15-year program, with capital outlays in excess of $100 million, and research and operating expenses likely to exceed four times that amount, will transform the nation’s ability to carry out earthquake engineering research, to obtain information vital to develop improved methods for reducing the nation’s vulnerability to catastrophic earthquakes, and to educate new generations of engineers, scientists and other specialists committed to improving seismic safety. The collaboration enabled through NEES and the explicit integration within its programs of experimentation, theory formulation and validation, data curation, model-based simulation, high performance computing and education will accelerate substantially the development of technically sound and cost-effective approaches to earthquake loss reduction.

The NEES initiative is part of the Major Research Equipment program at the National Science Foundation (NSF), comparable to the construction and operation of other major research tools, such as the South Pole Station, Laser Interferometer Gravitational-Wave Observatory, National Radio Astronomy Observatory, and so on. NEES is the first of these initiatives to be undertaken by the Engineering Directorate and incorporates several new and unique features.

When fully operational in October 2004, the NEES program will provide an unprecedented infrastructure for research and education, consisting of networked and geographically distributed resources for experimentation, computation, model-based simulation, data management, and communication. Rather than placing all of these resources at a single location, NSF has leveraged its investment and facilitated the integration of research and education by distributing the shared-use equipment among nearly 20 universities throughout the US. To insure that the nation’s researchers can effectively use this equipment, equipment sites will be operated as shared-use facilities, and NEES will be implemented as a network-enabled collaboratory. As such, members of the broad earthquake engineering community will be able to interact with one another, access unique, next generation instruments and equipment, share data and computational resources, and retrieve information from extensive digital libraries, without regard to geographical location.

Currently, four major activities are being undertaken to bring NEES on line. These include constructing the shared-use equipment sites, developing standards and advanced networking capabilities to connect the powerful new experimental and computational resources with the earthquake engineering community as well as to the public at large, developing a community-backed research collaboratory and consortium to carryout and manage NEES activities, and identifying a research agenda that addresses high priority needs.
The portfolio of test equipment includes major new or upgraded shaking tables, reaction wall facilities, geotechnical centrifuges, tsunami wave tanks, and mobile field test equipment. Shared-use sites are currently under construction at Oregon State University, Rensselaer Polytechnic Institute, University of Buffalo, University of California campuses at Berkeley, Davis and Los Angeles, University of Colorado at Boulder, University of Minnesota, University of Nevada at Reno, and University of Texas at Austin. At each site, participation by off site collaborators is being encouraged through advanced capabilities for teleobservation and teleoperation. Additional NSF-funded sites will be announced in the near future, and other research facilities, nationally and internationally, are being invited to join NEES.

To enable broad-based collaboration by the earthquake engineering community using these facilities, recent advances in information technology and computer science are being adapted and extended. The systems being implemented will provide convenient, secure and dependable access to NEES resources. This system integration effort is led by the National Center for Supercomputer Applications headquartered at the University of Illinois at Urbana-Champaign, in conjunction with a consortium of other universities and national laboratories.

The NEES MRE is to be administered and managed by a single community-based and community-led consortium, and operated as a collaboratory. The NEES Consortium Development Project is being carried out by the Consortium of Universities for Research in Earthquake Engineering (CUREE), in cooperation with the Civil Engineering Research Foundation of the American Society of Civil Engineers, the Earthquake Engineering Research Institute, and other organizations.

NSF has funded two additional projects to help identify and prioritize the long-term uses of NEES. One of these efforts, being undertaken by the Earthquake Engineering Research Institute, focuses on identifying the overall research needs for reducing earthquake losses, and the other, conducted by the National Research Council, focuses on the specific uses of NEES. Information on all of these in-progress NEES activities is available at: www.nees.org.

By bringing researchers, educators and students together with members of the broad earthquake engineering and information technology communities, providing them ready access to powerful experimental, computational, information management and communication tools, and facilitating their interaction as if they were “just across the hall,” the NEES Collaboratory will be a powerful catalyst for transforming the face of earthquake engineering. The diversity of talents, backgrounds, experience and disciplinary concerns to be represented within the NEES Collaboratory will provide an unparalleled stimulus to intellectual inquiry and education. The NEES Collaboratory will fundamentally change the processes by which earthquake engineering research is initiated and performed, accelerate the generation and dissemination of basic knowledge, facilitate the development of effective educational programs, minimize the lag between knowledge development and its application, and hasten the attainment of the nation’s goals for earthquake loss reduction.
The New Phase of Structural Control

Structural control technology might be accomplished for the present phase with the appearance of “Semi-active control system,” which realizes the goal of controlling structural response during extremely large earthquakes.

In its essential objective, buildings where control systems are installed should operate with their required performance against any kind of earthquakes through their whole lifetime, though the large earthquake’s occurrence is quite uncertain. For this purpose, regular maintenance is necessary and important due to the reason that the control systems are supported by many electronic components and computer systems which are required to check and confirm their performance with short time intervals compared with the longevity of buildings. Though the Active Mass Driver (AMD) and Active Variable Stiffness (AVS) systems were the first challenging applications to actual buildings, at the same time, the maintenance and replacement of these systems brought a heavy economic burden for the buildings’ owners to continuously maintain and replace components.

However, this will provide us with another opportunity to find further possibility of application of the concept of structural control. The structural control system should be used not only for the mitigation of earthquake hazard aiming at structural safety of buildings as well as keeping their functions, but also the usual tasks of daily life like building management. For instance, if the control system could be applied to the equipment used daily for facility management, the system would be maintained with higher reliability and insurance.

Such a concept goes back to the proposal of a “dynamic intelligent building” which was described in the State-of-the-Art-Report, the Ninth World Conference on Earthquake Engineering in 1988. The author emphasized the importance of structural intelligence to improve their constitution and to protect the safety of the building with the structural control system from unpredictable large earthquakes.

The time has come when we should open the door to a new phase of structural control by the integration of the developing concept of structural control with daily facility and building management systems. If we could realize such integration in the future, the concept will not only ensure the structural safety of individual buildings but also global safety of community or urban regions.
The OpenSees Software Framework for Earthquake Engineering Simulation

A key aspect in the development of performance-based earthquake engineering methodologies is improving the capability of engineers to simulate the performance of structural and soil-structure systems in an earthquake. Simulation involves the development of calibrated mathematical models to represent the behavior of the system, the numerical computation to solve the governing equations, and the processing of the results to interpret the performance of the system. The past twenty-five years witnessed important and wide-ranging research advances in this regard. Structural and geotechnical engineers use a variety of specialized or general software packages depending on the appropriateness of the mathematical models implemented in the software, the available computational resources, and individual or organizational experience and policies. In research there are tremendous needs for improvements in simulation methods by developing new models, computational procedures, and methods of performance visualization. Individual researchers often use customized versions of specialized codes or work within the limits imposed by commercial, general-purpose codes.

Current software makes it difficult for researchers and developers to improve simulation methods by taking advantage of rapid changes in parallel and distributed processing, networking, databases, visualization, and entirely new approaches to computing such as application service providers, peer-to-peer computing and computational grids. The limited ability to exchange and communicate software implementations of models and computational methods is a significant impediment on research and on transfer of new methods to engineering practice.

From the perspective of an engineer conducting a simulation, there are a number of desirable requirements. There should be the capability for using, selecting, and sharing models for materials, elements, components, and entire substructures. The models should be independent of the simulation methods used to compute the state of the model so as to provide flexibility in how simulations are performed. There should be interfaces between models, databases, and visualization tools to provide capabilities for interrogating and investigating the model and results of the simulation. Furthermore, the simulation should support capabilities for system identification studies, optimization, and reliability, all of which will become increasingly important techniques for performance-based earthquake engineering design.
To address the research and engineering application needs for improved simulation software, the Pacific Earthquake Engineering Research Center is developing the Open System for Earthquake Engineering Simulation. OpenSees is an enabling technology in PEER’s mission to develop performance-based earthquake engineering methodologies. The software is called a framework because it is an integrated collection of software components used to build simulation applications. OpenSees is not a “code” by the usual definition of a program to solve a specific class of problems. Rather it involves a set of classes and objects that represent models, perform computations for solving the governing equations, and provide access to databases for processing of results. At its most fundamental level, OpenSees can be viewed as a set of objects that are accessed through a defined application program interface (API). The framework was designed using object-oriented principles, and is implemented in C++, a widely used object-oriented programming language. The development of OpenSees is open-source, meaning that all versions of the program, documentation, examples, are available for anyone interested in using and contributing to the development.

The OpenSees website at http://opensees.berkeley.edu/ contains information about the program and an online version control system for the software. The typical use of OpenSees is through an interface language, called Tcl/Tk, which allows high-level specification of the model, analysis procedure, and post-processing steps. Tcl/Tk scripts are fully programmable themselves and are more general than typical input languages used in codes. Other approaches, including graphical and visualization interfaces to OpenSees are under development. Web-based access to models and results of simulations are being developed and will likely become an important way to conduct simulations in the future.

The development of OpenSees is supported by a National Science Foundation grant to PEER. A large number of faculty, researchers, and students in PEER have contributed to the OpenSees development, including but not limited to Filip Filippou, Frank McKenna, Gregory Deierlein, Boris Jeremic, Michael Scott, Jun Peng, Kincho Law, Terje Haukass, Joel Conte, and Ahmed Elgamal.
An Illustrated
Biographical Sketch:
Ray Clough
Dr. Ray Clough  
Nishkian Professor of Structural Engineering, Emeritus  
University of California, Berkeley
Dr. Ray W. Clough joined the faculty of the University of California at Berkeley as Assistant Professor of Civil Engineering in July 1949. He was promoted to Full Professor in 1959 and served from 1967-1970 as Chairman of the Division of Structural Engineering and Structural Mechanics.

Throughout Dr. Clough’s professional career he has specialized in structural dynamics and earthquake engineering and has done extensive research on the development of digital computer methods for the analysis of complex problems in these fields. In 1961 he received a Research Prize from the American Society of Civil Engineers for his work in earthquake engineering, and in 1970 received the Ernest E. Howard Award from the ASCE for development in the finite element method and its application to civil engineering problems. In 1956-57 he received a Fulbright Fellowship to do research in ship vibrations in Trondheim, Norway; in 1963-64 he received an Overseas Fellowship from Churchill College, Cambridge University, England; in 1968 he was elected to membership in the National Academy of Engineering; in 1970-71 he was appointed as a Miller Research Professor at the University of California, Berkeley, and was later appointed to the Nishkian chair.

Professor Clough has traveled extensively on earthquake engineering work, having surveyed the damage caused by the Agadir, Morocco and Chilean earthquakes of 1960, and the Skopje, Yugoslavia earthquake of 1964. He was a member of the UNESCO Seismology and Earthquake Engineering Mission to the Mediterranean Area in 1962, a member of the U.S. delegation to the UNESCO Governmental Meeting on Seismology and Earthquake Engineering at Paris in 1964, and a member of the U.S. delegation to inspect earthquake engineering research and construction in the U.S.S.R. in 1969.

Dr. Clough has served on many governmental advisory panels and boards, representing the technical areas of earthquake engineering and structural dynamics, including the Committee Advisory to ESSA, the Panel Advisory to the Building Research Division NBS, the Corps of Engineers Structural Design Advisory Board, and the Redwood City Seismic Advisory Board. He also served actively in professional societies: as chairman of the Executive Committee, Engineering Mechanics Division ASCE, and as a member of the Board of Directors of the Structural Engineers Association of Northern California; of the seismological Society of America, and of the Earthquake Engineering Research Institute (2 terms). In addition, he served as General Editor of the International Journal of Earthquake Engineering and Structural Dynamics. He is a recipient of the ASCE von Karman Medal and the National Medal of Science.

Throughout his professional career he has been retained as consultant on complex structural dynamics problems in the design of nuclear reactor power stations, multistory buildings and towers, offshore drilling platforms and similar specialized projects.
Ray W. Clough, Jr. in 1925. Age 5 years; in front of his parent’s house at 1403 East 65th Street, Seattle, WA.

All photographs of Professor Clough not otherwise credited are printed here courtesy of Ray Clough.
Lt. R.W. Clough, at work in his office.  April 20, 1944
Caltech, Pasadena, CA

Ray with son Doug, and daughters Allison and Meredith
Family camping trip. Yosemite, 1955
Ray Clough receiving Honorary Doctorate
Goteborg, Sweden, 1979

Ray Clough speaking to King Karl Gustav
After receiving Honorary Doctorate
Goteborg, Sweden, 1979
Foreground: Egor Popov, Joseph Penzien, and Ray Clough
India, 1977

Ray and Shirley Clough
Alaska, 1993
At the retirement party for Joseph Penzien, 1988;  
L. to R.: Mr. & Mrs. Bob Wiegle; Rolly Todd and Ray Clough

Joseph Penzien (left) and Ray Clough (to his left)
The UC Berkeley shake table nearing completion in 1969 at the Richmond Field Station. Dixon Rea is shown on the platform, which measures 20 ft. by 20 ft. in plan. Photo credit: UCB Earthquake Engineering Research Center.

While this was the most sophisticated such simulator in the world at the time and for many years afterward, it was only a “medium-scale” piece of equipment as compared to the proposal from UC Berkeley at the time for a “large-scale” table 100 feet square, which was never funded. (J. Penzien, J. G. Bouwkamp, R. W. Clough, Dixon Rea, Feasibility Study Large-Scale Earthquake Simulator Facility. UC Berkeley Earthquake Engineering Research Center, EERC-67-1, September, 1967). The performance specifications for the 1960’s-era large-scale earthquake simulator design indicate the far-reaching vision of Professor Penzien, Professor Clough, and their Berkeley colleagues. It was to have actuators to generate accelerations along both horizontal axes and also vertically; a specimen mass of up to 4 million pounds; and it was to be housed in a laboratory building 200 ft. x 200 ft., with the entire structure to be movable to cover or uncover the test area and adjacent work areas as desired, like an early version of one of today’s sports stadium roofs.
To Ray Clough
Best Wishes

Experimental Study of Masonry Walls, 1970’s

the UC Berkeley - CUREE Symposium
in Honor of Ray Clough and Joseph Penzien

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Awards and Honors

1956-57  Fulbright Research Fellowships to Norway
1961    ASCE Research Prize
1963-64  Churchill Overseas Fellowship, Cambridge University
1968    Member, National Academy of Engineering
1970    Ernst Howard Award, ASCE, 1970
1970-71  Miller Research Professorship, University of California, Berkeley
1972    “Honorary Researcher,” National Civil Engineering Laboratory, Lisbon, Portugal
1972-73  Fulbright Research Fellowship to Norway
1974    Member, “Det Kongelige Norske Videnskabers Salskab” (The Royal Norwegian Scientists Society)
1979    Member, National Academy of Sciences
1979    Nathan M. Newmark Medal, ASCE
1979    Honorary Doctor of Technology, Chalmers University, Sweden
1980    Moissieff Medal, ASCE
1982    Honorary Doctor of Technology, Norwegian Institute of Technology, Trondheim
1983    Nishkian Professor of Structural Engineering, University of California, Berkeley
1986    International Association of Computational Mechanics, First Congress Medal
1987    Berkeley Citation, University of California at Berkeley
1988    Honorary Member, American Society of Civil Engineers
1994    National Medal of Science
1996    Theodore von Karman Medal, ASCE for engineering mechanics achievements

the UC Berkeley - CUREE Symposium
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Publications

JOURNALS


* Also published as: Klaf, R.U, - Metod konecinovo elementa v resenii ploskoi zadaci teorii uprugosti, fn; “Rasciot stroitelinth konstruktii s primenien elektronnth masin,” (Design of Structures with Application to Electronic Computers), Moskva, Stroiizdat, 1967.

** Also published in Bulletin RILEM, No. 10, June 1963.


90. “Predicting the Earthquake Response of Reinforced Concrete Structures,” accepted for publication in Proceedings, ACI Symposium on Reinforced Concrete Structures in Seismic Zones.


100. “Earthquake Engineering Research at the University of California,” Proceedings, 45th Annual Convention, Structural Engineers Association of California, September 1976.


114. “Shaking Table Earthquake Response of Steel Frame,” with D. T. Tang, Journal of the Structural Division, ASCE Vol. 105, N.-


Engineering, Stanford, CA, August 1979.

119. “Nonlinear Earthquake Response Behavior of Arch Dams,” Proceedings, Research Conference on Earthquake Engineering, U.S.-
Yugoslavia Cooperative Board, Skopje, Yugoslavia, June 1980.

120. “Earthquake Simulator Research on Arch Dam Models,” with Akira Niwa, Proceedings, Symposium on Dynamic Modeling of
Concrete Structures, ACI Spring Conference, Las Vegas, NV, March 1980.

121. “Biaxial Shaking Table Study of a R/C Frame,” (with M. G. Oliva), Proc., 7th World Conference on Earthquake Engineering, Vol.


123. “Buckling of Cylindrical Liquid Storage Tanks under Earthquake Loading,” (with A. Niwa), Earthquake Eng’g. and Structural

124. “Nonlinear Seismic Response of Arch Dams,” (with A. Niwa), Earthquake Eng’g. and Structural Dynamics, Vol. 10, No. 2,
March-April 1982.


126. “Earthquake Simulator Research on Arch Dam Models,” (with A. Niwa), American Concrete Inst. Special Publication, 73-5,
1981.

127. Papers in Proc. 7th European Conference on Earthquake Engineering, Athens, Greece, September 1982:

   (a) “Buckling in Seismic Responses of Cylindrical Liquid Storage Tanks,”
       (with Akira Niwa), Vol. 6, pp. 223-233.

   (b) “Shaking Table Study of a Tubular Offshore Platform Frame,” (with
       Yusot Ghanaat), Vol. 6, pp. 279-291.

   (c) “Experimental Investigation of a Cylindrical Tank Under Earthquake
       Loading,” (with George Manos), Vol. 6, pp. 233-240.

128. “Response of a Cylindrical Liquid Storage Tank to Static and Dynamic Lateral Loads,” (with George Manos), Earthquake Ground

129a. Also printed in 60th Anniversary Volume for Dr. Bruno Thurlimann, E.T.H., Zurich, June 1983.


RESEARCH REPORTS


37. “Shaking Table Research on Arch Dam Models,” (with A. Niwa), Report No. UCB/EERC 80/05, Earthquake Engineering Research Center, University of California, Berkeley, September 1980.

38. “Evaluation of a Shaking Table Test Program in Response Behavior of a Two-Story R.C. Frame,” (with J. M. Blondet and S. A. Mahin), Report No, UCB/EERC 80/42.


42. “Dynamic Response Behavior of Quan Shui Dam,” (with five others), University of California, Earthquake Engineering Research Center, Report No. UCB/EERC-84/20, November 1984.

43. “Shaking Table Tests of Large-Panel Precast Building System Assemblages,” (with M. G. Oliva), University of California, Earthquake Engineering Research Center, Report No. UCB/EERC-83/14, June 1985.


BOOKS


An Illustrated
Biographical Sketch:
Joseph Penzien
Dr. Joseph Penzien
Professor Emeritus of Structural Engineering
Dr. Penzien is a Professor Emeritus of Structural Engineering of the University of California, Berkeley (UCB), where he served 35 years in the Department of Civil Engineering specializing in the areas of dynamics of structures and earthquake engineering. He was the founding Director of the University's Earthquake Engineering Research Center (EERC) having responsibility for its research and laboratory development programs, including design of the earthquake simulator (shaking table) facility at the UCB Richmond Field Station.

Since 1982, Penzien has actively participated in numerous engineering projects in Taiwan, assuming major responsibility in setting seismic design criteria and assisting in seismic response and performance evaluations of numerous important engineered facilities including:

(1) Taipei Rapid Transit System, working through the American Transit Consultants, Inc. (ATC),
(2) Kaoshuing Cross-Harbor Tunnel, providing services to China Engineering Consultants, Inc. (CECI),
(3) Sungshan Railway Extension, again providing services to CECI,
(4) Feitsui and Techi Arch Dams, serving as consultant to Sinotech Engineering Consultants, Inc. (SEC),
(5) National Chung Cheng University being built in the city of Chiayi, Taiwan, formulating seismic design criteria for new construction,
(6) Fifty-Story Shin Kuan Insurance Building in downtown Taipei, setting seismic design criteria and conducting dynamic response analyses,
(7) Taiwan Power Company’s (TPC’s) Nuclear Power Plants, developing site-specific response spectra and conducting seismic hazard analyses, and
(8) Nuclear Power Plant Containment Building Model (1/4-scale), Lotung, Taiwan, conducting soil-structure interaction analyses and correlating results with field-test data under the joint TPC/EPRI program.

He has also served Tokyo Electric Power Services Company, Ltd. (TEPSCO) during the past fifteen years, providing assistance and advice on earthquake engineering related projects. While serving in this capacity, he has guided the development of numerous computer programs, including Computer Programs HASSI-1 through HASSI-8 for evaluating three-dimensional soil-structure interaction effects.

Penzien has served as Vice Chairman of Governor George Deukmejian’s Board of Inquiry on the 1989 Loma Prieta Earthquake; as Chairman of the Peer Review Panel on the Golden Gate Bridge, Seismic Retrofit Design Project, Phase II; Co-Chairman of Technical Coordinating Committee of U.S./Japan Cooperative Research on Large-Scale Testing of Building Structures; as a member of the Oversight Committee, California Universities for Research in Earthquake Engineering; as a member of the Brookhaven National Laboratory Expert Panel to review JEEAG4601 “Technical Guidelines for Aseismic Design of Nuclear Power Plants;” as a member of the Peer Review Panel on the Golden Gate Bridge Seismic Retrofit Design Project, Phase III, as Chairman of the Seismic Advisory Board, Bronx-Whitestone Bridge Seismic Investigation in New York, as a member of the Board of Consultants to Bechtel Corporation on the San Francisco MUNI Metro Turnaround Project, as a member of the Project Engineering Panel of the Applied Technology Council ATC-32 Project “Review and Revision of Caltrans Seismic Design Procedures for Bridges,” as a member of the Oversight Panel, Proposition 122 Research and Development Plan, California Seismic Safety Commission, and as a member of technical review panels for the Mokelumne Aqueduct seismic upgrade study project and the seismic evaluation of the Lafayette Reservoir intake/outlet tower project for the East Bay Municipal Utility District (EBMUD). Currently, he is serving as Chairman of the Seismic Advisory Board, California Department of Transportation, as a consultant to Bay Area Transit Consultants on the Bay Area Rapid Transit (BART) San Francisco Airport Extension Project, as a member of the Highway Seismic Research Council, Technical Group, National Center for Earthquake Engineering, State University of New York at Buffalo, as a consultant to Parsons Brinckerhoff on the seismic retrofit of the Macombs Dam Bridge and the 145th Street Bridge in New York City, as a member of the Technical Advisory Panel to T. Y. Lin International/Moffatt and Nichol Joint Venture on the design of the new San Francisco-Oakland Bay Bridge East Crossing, and as a member of the Parsons Brinckerhoff Seismic Review Panel, Cooper River Bridges, Charleston, S.C.
I attended a country one-room schoolhouse having one teacher teaching all eight grades. The picture shows me in the center holding the owl’s head. The owl was shot by an older brother of my father, because the owl was attacking our chickens.

- JP

All photographs of Professor Penzien not otherwise credited are printed here courtesy of Joseph Penzien.
My brother Bill (sitting on the radiator) and I (pumping up a flat tire) spent much time keeping the old Model T Ford running. We patched the inner tubes in the tires so many times we finally gave up and stuffed the tires with straw. The picture was taken about 1935 or 36.

- JP

My father and mother, John Chris and Ella May, my two brothers John (tallest one) and Bill (back center), my two sisters Mannie (front center) and Gladys (front right), and I (front left). 1941

- J.P.
My first job after graduating from the University of Washington was with the Corps of Engineers at Bonneville, Oregon where the Bonneville Dam on the Columbia River is located. I worked in the hydraulics laboratory on model testing of the Umatilla, Oregon Dam (now called McNavy Dam). In the picture I am standing on a walkway leading to the lab. Fall 1945.

- J.P.
Jeanne Hunson (first wife) shown in this picture, 1950.

Joseph Penzien and Senator Cranston at the Richmond Field Station shortly after completion of the shaking table facility.

the UC Berkeley - CUREE Symposium in Honor of Ray Clough and Joseph Penzien
The UCB shaking table at RFS was the first of its kind in the world. Kajima Corporation came to the RFS to be briefed on the design of our system. Then went back to Japan and built a shaking table nearly equivalent to ours at UCB/RFS. Dr. Muto (far left) and Dr. Hisada of Kajima requested that Dixon Rea (third from left) and I (fourth from left) come to Japan to check out their system and put it into operation. Dixon was a key person in the design of our system.

- J.P.

Professor Penzien with Professor Popov (far right) and others at a dinner held in honor of UCB Noble Prize Winner Professor Lee of Taiwan (who is now President in Taiwan). Hosts of the dinner were T.Y. Lin and Chancellor Tien.
A dinner party at Frieder Seible’s mountain home outside San Diego attended by Caltrans Seismic Advisory Board Members (shown in the picture left to right, F. Seible with only arm showing, Joe Nicoletti, Joseph Penzien, Bruce Bolt, I.M. Idress, and Jim Roberts.

Photo courtesy of T. Kaminosono

1970’s group photo of American and Japanese research collaborators in Tsukuba, Japan

Photo courtesy of T. Kaminosono

the UC Berkeley - CUREE Symposium
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I was very fortunate to meet Mi-Jung Park at a social function in Seoul, Korea in 1986. She was working at Korea’s museum of modern art at the time. We married June 16, 1988 very shortly after I retired from UCB. This picture was taken in Tokyo shortly after we were married. She made the dress she is wearing. She has since graduated from the California College of Arts and Crafts with a Bachelor of Fine Arts degree. She now keeps busy as a painter of oil and watercolor paintings.

- J.P.
Awards and Honors

1959  NSF Post Doctoral Fellowship
1965  Research Prize, ASCE
1969  NATO Senior Science Fellowship
1973  NSF Senior Science Fellowship
1977  Elected Member, National Academy of Engineering
1978  Elected Fellow, American Academy of Mechanics
1979  Elected Honorary Member, Peruvian Association of Earthquake Engineering
1980  Silver Medal of Paris
1983  Nathan M. Newmark Medal, ASCE
1986  Alfred M. Freudenthal Medal, ASCE
1986  Elected Honorary Member, Earthquake Engineering Res. Inst., USA
1986  Elected Honorary Member, Architectural Institute of Japan
1988  The Berkeley Citation
              (Highest Award given by the University of California, Berkeley)
1989  Elected Honorary Member, ASCE
1992  Elected Honorary Member, International Assoc. of Earthquake Engineering
1993  Housner Medal, EERI
1996  Alfred E. Alquist Medal, California Earthquake Safety Foundation
1997  Elected Fellow, California Council on Science and Technology
2000  EERI Distinguished Lecturer for year 2000
Publications

TECHNICAL PAPERS


33. “Earthquake Engineering Research at University of California, Berkeley,” (Served as Coordinator of the U.S. Participants of this Seminar), Proc., U.S.-Japan Sym. on Earthquake Eng., Sendai, Japan, September 1970.


40. “Structural Research Using an Earthquake Simulator,” (with D. Rea), Proc., 1972 Annual Convention, Structural Engineers Assoc. of California, October 1972.


104. “Introduction to U.S.-Japan Cooperative Earthquake Engineering Program,” (with H. Umemura, M. Watabe, and R. Hanson), Publication SP-84, American Concrete Institute, Earthquake Effects on Reinforced Concrete Structures, James K. Wight, Editor, 1984.


121. “Multiple-Station Ground Motion Processing and Simulation Based on SMART-1 Array Data,” (with H. Hao and C.S. Oliveira), Nuclear Engineering and Design III (1989) 293-310, North-Holland, Amsterdam.


TECHNICAL REPORTS

1. “Behavior of Reinforced Concrete Beams Under Long Duration Impulsive Loads,” (with R. J. Hansen), Report to the Corps of Engineers, Department of the Army, MIT, June 1948.


4. “A Discussion of the Dynamic Analysis of a Frame Subjected to an Impulsive Load,” (with H. A. Williams), Report to the Corps of Engineers, Department of the Army, MIT, August 1950.


27. “Seismic Analysis of the Charaima Building, Caraballeda, Venezuela,” (Chairman of Subcommittee of Structural Engineers Association), Report No. UC-EERC 70/4, Earthquake Engineering Research Center, University of California, Berkeley, August 1970.


42. “Correlative Investigations on Theoretical and Experimental Dynamic Behavior of a Model Bridge Structure,” (with K. Kawashima), Report No. UC-EERC 76/26, Earthquake Engineering Research Center, University of California, Berkeley, July 1976.


64. “Vibrations of Elevated Structures and Bridges Caused by High Speed Train Loadings,” by Wen S. Tseng, Joseph Penzien, and Dr. Kang, Kee-Dong, August 1994


COMPUTER PROGRAMS

1. Earthquake Engineering, Chapter 13: Application of Random Vibration Theory (pp. 335-347), and Chapter 14: Soil-Pile Foundation Interaction (pp. 349-381), 1970.


