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Evaluation of Bridge Damage Data from Recent Earthquakes

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This article presents research resulting from NCEER's Highway Project, task 106-E-7.3.3. It is based on a technical paper submitted for inclusion in an annual report to the Federal Highway Administration summarizing Research Year 3 of the Seismic Vulnerability of Existing Highway Construction project. Comments and questions should be directed to Anne Kiremidjian, Stanford University, at (415) 723-4164; email: ask@ce.stanford.edu.

Data on bridge damage from earthquakes is becoming increasingly more available. Such data, however, have not been systematically studied to evaluate damage characteristics and correlate these to observed or estimated local ground motions. In this task, data on bridge damage from the Loma Prieta and Northridge earthquakes were studied to correlate observed bridge damage to:

- Structural characteristics of a bridge
- Local ground motions
- Repair cost

In order to achieve these objectives, statistics on structural characteristics of bridges, ground shaking levels at bridge sites, damage characteristics and repair cost were obtained. Next, empirical damage probability matrices and fragility curves were developed from data on bridge damage. In addition, correlation between structural characteristics and observed damage were determined.

Despite the high ground motion levels observed in the 1994 Northridge, California earthquake, only about 3% of all the bridges in the area experienced major damage. The analyses of bridge damage data showed that concrete structures designed/built with older design standards were more prone to damage under seismic loading. The ground shaking level, skew angle, abutment type, pier type and span continuity showed the highest correlation with observed damage. The total repair cost for the damaged bridges was about $150,000,000, with repair and/or reconstruction of the collapsed structures forming a large portion of the total.

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Bridge Damage Data Analysis Method

Characteristics of the Database

The database compiled for the Loma Prieta and Northridge earthquakes consists of four main types of data: (a) structural characteristics, (b) bridge damage, (c) repair cost, and (d) ground motion levels and soil characteristics at bridge sites. A relational database management system (RDBMS), dBase™, was used to compile and perform queries for data on bridge damage and structural characteristics of bridges. In addition, a geographic information system (GIS), Arc/Info™, was used to obtain the ground motion levels at each bridge site.

Structural Characteristics: Structural characteristics compiled for the groups of bridges that were exposed to ground shaking included abutment type, number of spans, type of superstructure and substructure, length and width of the bridge, skew, number of hinges at joints and bents, abutment and column foundation types, retrofit history, and design year to represent design standards, such as column reinforcement and seat width. These structural characteristics were obtained from the Structural Maintenance System (SMS) database compiled and managed by Caltrans (Caltrans, 1993). In addition, more detailed information was obtained from Caltrans for some of the damaged bridges. Caltrans is currently in the process of compiling a database that includes information on abutment, bent/pier/column and bent/pier/footing details, such as seat width and type of bearings, footing type and column/footing connection. However, only about 15% of all the California bridges are currently in this database, thus this detailed information could not be used in the statistical analyses.

Bridge Damage: Detailed damage descriptions and the corresponding damage states were compiled for bridges damaged in the two earthquakes. The damage descriptions were obtained mainly from bridge damage reports compiled by Caltrans (1989, 1994). For the Northridge earthquake, these descriptions were cross-referenced with those provided by Buckle (1994), EERI (1995), and Yashinsky (1995). Judgment was used to treat inconsistencies in the interpretation of the observed damage data.

The database on bridge damage specifies two damage states (*minor, major*) for bridges damaged in the Loma Prieta earthquake, and four damage states (*minor, moderate, major* and *collapse*) for those damaged in the Northridge earthquake. The bridge damage data were used in correlation studies to obtain ground motion-damage relationships.

Damage State Definitions: Currently, no guidelines for evaluating physical bridge damage exist. The terms *minor*, *moderate* and *major* damage were subjective. Definitions of damage states for columns, abutments, and joints and connections for concrete bridges are proposed which were developed based on the observed bridge damage in the Northridge earthquake (Basöz, 1996). A questionnaire was prepared to acquire expert opinion on the proposed damage state definitions and given to bridge engineers at Caltrans. The feedback provided by the bridge engineers will be used to modify some of the damage state definitions.

Repair Cost: The estimated repair cost values for damaged bridges were obtained from supplementary bridge reports compiled by Caltrans following each earthquake. The database includes total estimated repair cost and more detailed information on repair work and cost for each bridge that was repaired. The repair cost ratio, defined as the ratio of repair cost to replacement cost of a bridge, was calculated for all the damaged bridges. The replacement cost of a bridge was estimated to be $\$90/ft^2$ based on the 1995 cost books.

Ground Motion Levels: In addition to structural characteristics, soil type at each bridge site and peak ground acceleration (PGA) levels observed in the two earthquakes were compiled. In order to obtain empirical ground motion-damage relationships for the set of bridges damaged in the Northridge earthquake, two sets of peak ground acceleration (PGA) values were used as the ground motion levels: (a) PGA values reported by USGS (1994), which were obtained from the contours of observed PGA recordings in the horizontal direction and (b) PGA values reported by WCFS (1995) that were obtained from the contours of the average of the PGA values measured in the E-W and N-S directions. Recorded ground motion levels were used to scale the parameters of empirical Green's functions which were used in simulating the ground shaking levels (Somerville et al., 1996). The PGA value at a given bridge site was obtained within GIS by overlaying the ground shaking map and the bridge location map. Subsequently, the highest PGA values obtained at a bridge site were 1.55g and 0.66g for the USGS and WCFS maps, respectively. Since the PGA levels from the two data sets varied considerably, correlation studies were performed for both data sets. Because no contour maps were available for the PGA levels observed during the Loma Prieta earthquake, attenuation relationships were used to estimate the level of ground shaking at each bridge site.

Classification of Bridges

The compiled inventory of bridges was reviewed to: (a) select bridges to be used in correlation studies, (b) select structural characteristics (attributes) that best describe the seismic response of bridges, and (c) verify the correctness of the attribute values included in the bridge inventory database.

Data Sets: Several data sets were used for statistical analyses. All the analyses were performed for the state bridges since most of the reported damage in both earthquakes pertain to state bridges. First, all highway state bridges were selected and gathered in the *highway bridge data set*, and statistics on design year and ground shaking levels were obtained. Most of the bridge damage pertained to concrete structures. The number of damaged steel bridges was not large enough for statistical analysis. Therefore, concrete bridges were selected from the *highway bridge data set*.

One of the objectives of this research was to identify the effect of various structural characteristics on bridge damage. In order to study the effect of structural component types on bridge damage, such as effect of abutment type (monolithic or non-monolithic), and effect of number of columns per bent, bridges with single abutment type and one column bent type were compiled in a database called the *homogeneous data set*. That is, in order to determine the effect of each characteristic, only bridges with homogeneous structural characteristics were selected from the *concrete highway bridge data set*. For example, a bridge with a seat type abutment (non-monolithic), and a diaphragm type (monolithic), was defined as a *heterogeneous* bridge and excluded from the *homogeneous data set*. Similarly, a bridge with both multiple and single column bents was defined as a heterogeneous bridge, and was excluded from the *homogeneous data set*. Bridges with incomplete information were also excluded.

Another criterion in the data selection relates to the correlation analyses. A complete data set for correlation analyses requires that all the bridges exposed to a given ground shaking level be included. In order to satisfy this requirement, a minimum PGA level was selected as a threshold value. This PGA level was determined based on the available ground motion maps. The data set that satisfies this condition was extracted from the *homogeneous data set* and is referred to as the *correlation data set*.

The bridges in the *correlation data set* were grouped first by the superstructure type and substructure material. Then, these bridges were further classified into subcategories based on other structural characteristics, such as number of spans, abutment type, column bent type and span continuity. The classification scheme used in this task was adapted from the bridge classification developed by Basöz and Kiremidjian (1996) under another NCEER project. The damaged bridges were classified to group bridges together that were expected to experience similar damage levels under a given seismic loading. The correlation studies were also carried out using the bridge classification defined by the National Institute of Building Sciences (NIBS) Manual (RMS, 1995).

Reliability of the Database: Caltrans currently has two database systems: the first one (SMS) follows the Federal Highway Administration (FHWA) National Bridge Inventory System but is more detailed, and the second one (BIRIS) is a database that stores bridge books and drawings for all the bridges. The bridge books include detailed reports from each bridge inspection. For some of the 25,000 bridges in the state of California, discrepancies exist between the two databases.

The two databases were compared to verify the correctness of the attribute values for some of the bridges that were damaged in the Northridge earthquake. The abutment type and column bent type were found to be more likely to have errors than the other attributes of interest for this research. For example, in only a few cases (for 2 to 3% of the damaged bridge data set), the values of the design year and skew attributes were found to be incorrect. Where there were discrepancies between the two databases, the structural plans were investigated with the assistance of bridge engineers from Caltrans to determine the correct attribute values. In

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order to evaluate the effect of error inherent in the database on the results of the correlation studies, several analyses were performed using sample data sets with corrected and uncorrected data.

Correlation Studies

Correlation analyses were performed using the data on bridge damage and repair cost. The correlation studies were performed for the following objectives:

- To determine the structural characteristics that best represent damage such that bridges can be grouped using these characteristics,
- To obtain ground motion-damage relationships for bridges with similar structural characteristics,
- To obtain ground motion-repair cost ratio relationships to estimate direct economic losses due to damage to bridges,
- To correlate damage and repair cost ratio.

The data on bridge damage were compiled in the form of damage matrices, i.e., the number of bridges with each level of observed damage at different PGA levels. Then, the damage probability matrices (DPMs), i.e., the probability of being in a damage state given the ground motion level were obtained for each group of bridges. The damage matrices were used as input data to logistic regression analysis to obtain empirical fragility curves both unconditional and conditional on damage. Similar procedures were used to obtain empirical fragility curves for the repair cost ratio. Comparison of observed damage data to currently available ground motion-damage relationships (ATC, 1985; RMS, 1995) were presented in Basöz et al. (1997).

Example Statistics and Results

Some of the results based on data from the Northridge earthquake are presented in this section. The bridges in the Greater Los Angeles area including Los Angeles, Ventura, Riverside, and Orange Counties, were exposed to ground shaking during the 1994 Northridge earthquake. Table 1 lists the number of state and local bridges and the number of damaged state bridges in each of the four counties. A database that includes state and local bridges for the four counties was extracted from the Bridge Maintenance Database compiled by Caltrans (1993). Structural characteristics such as structural type and material, number of spans, abutment type, span continuity, design year indicating the seat width and column longitudinal reinforcement, substructure type, skew, and foundation type were included in this database.

Table 1: Distribution of State and Local Bridges and the Number of Damaged State Bridges in the Greater Los Angeles Area

County	No. of State Bridges	No. of Local Bridges	Total No. of Bridges	No. of Damaged Bridges
Los Angeles	2,097	1,553	3,650	228
Riverside	644	338	982	-
Orange	463	505	968	-
Ventura	329	175	504	5
Total	3,533	2,571	6,104	233

Bridge damage from the Northridge earthquake pertained mostly to state bridges in Los Angeles and Ventura Counties. Bridges in these two counties also experienced much higher accelerations than those in Riverside and Orange Counties. A total of 63 bridges were exposed to peak ground acceleration (PGA) levels of 0.15g or higher in Riverside and Orange Counties. As shown in Table 1, 3,533 state and 2,571 local bridges are located in the four counties. Of the 3,533 state bridges, 3,318 (1,902 bridges in Los Angeles County, 312 in Ventura County, 462 in Orange County and 642 in Riverside County) carry highway traffic and were included in the highway bridge data set. The number of bridges in the highway bridge data set by superstructure type and substructure material are shown in Table 2.

Figure 1 shows the distribution of these bridges by design

Table 2: Distribution of Highway Bridges in Los Angeles, Ventura, Orange and Riverside Counties by Structural and Material Type

	Concrete	Steel	N/A	Timber
Concrete Girder	2,396	9[1]	708	0
Steel Girder	119	3	32	0
Truss	4	0	0	0
Tunnel	0	0	4	0
Timber	0	1	0	4
Arch	12	0	15	0
Suspension	1	0	0	0
Unknown	4	0	6	0

[1] These nine bridges have concrete slab type superstructure and have both concrete and steel column bents.

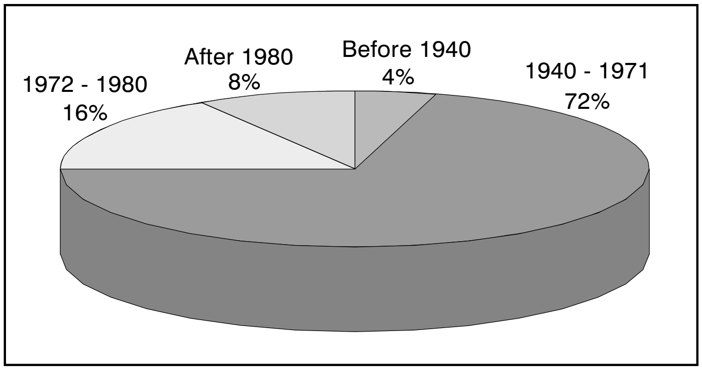

Figure 1: Distribution of State Highway Bridges in Los Angeles, Ventura, Orange and Riverside Counties by Design Year

year. Seventy seven percent of the bridges in the highway bridge data set were designed by pre-1971 design standards. The majority of bridges in the four counties were concrete structures (see Table 2) as were more than 85% of the damaged bridges. Therefore, the statistical analyses were conducted mainly for concrete bridges. Figure 2 shows the recorded PGA values (USGS, 1994) and the bridges in Los Angeles, Ventura, Orange and Riverside counties. The PGA value at a given bridge site was obtained within GIS.

Figure 3 shows the distribution of damaged bridges by design year and damage state. Seventy seven percent of the damaged bridges were designed with pre-1971 design standards. Eighty percent of the damaged bridges were multiple span bridges. Figures 4 and 5 show fragility curves for multiple span bridges. Note that the empirical fragility curves shown

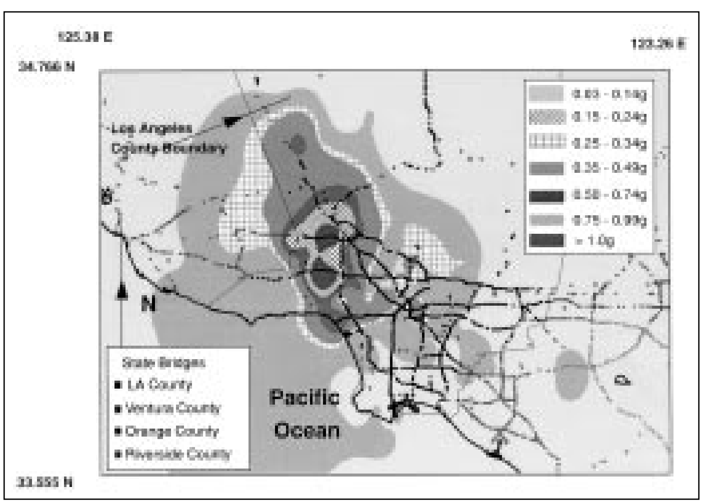

Figure 2: PGA levels observed in the Greater Los Angeles area from the Northridge earthquake (USGS, 1994)

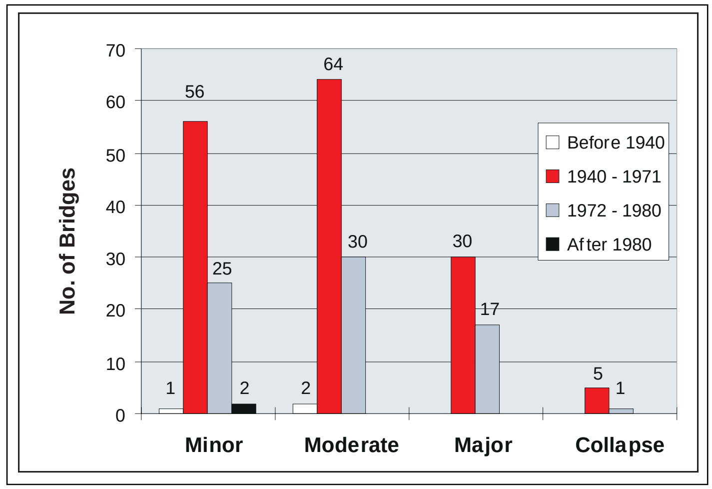

Figure 3: Distribution of All Damaged Bridges by Design Year and Damage State

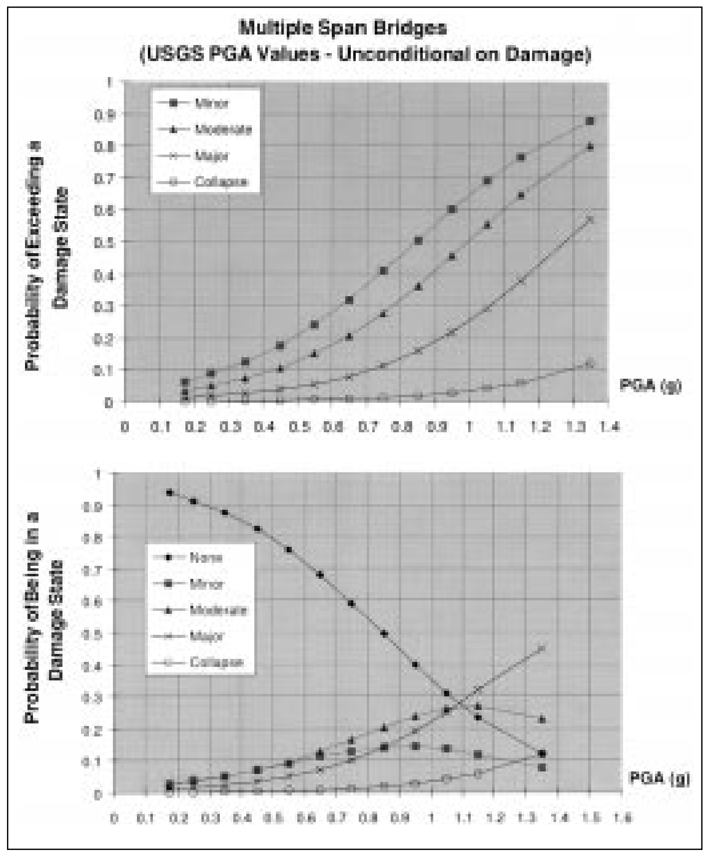

Figure 4: Empirical Fragility Curves for Multiple Span Bridges, Unconditional on Damage

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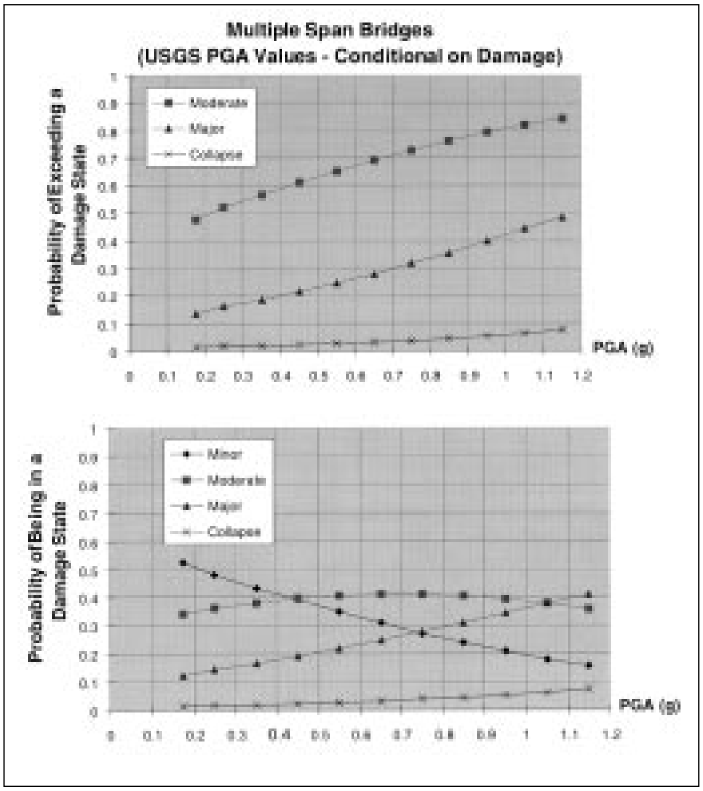

Figure 5: Empirical Fragility Curves for Multiple Span Bridges, Conditional on Damage

in Figure 5 are conditional on damage, i.e., they show the probability of being in (or exceeding) a particular damage state given a bridge is damaged. The PGA values shown on the horizontal axis are the observed values reported by USGS (1994).

For the repair cost data, a database was compiled from the supplementary bridge damage reports provided by Caltrans. A total of about $150,000,000 was reported as repair cost in these reports. The total repair cost for the six collapsed bridges constitute 75% of the repair cost of all damaged bridges. The database includes total estimated repair cost and more detailed information on repair work and cost for 130 bridges in Los Angeles and Ventura counties. Table 3 shows the estimated repair cost of damaged bridges by damage state. Figure 6 shows fragility curves for repair cost ratio for multiple span bridges.

Table 3: Distribution of Estimated Repair Cost by Damage State

Damage State	Number of Bridges	Estimated Repair Cost
Collapse	6	$121,765,750
Major	47	$18,398,057
Moderate	93	$6,895,731
Minor	85	$446,950

Concluding Remarks

The results from this task can be used to assist in making decisions about mitigation, such as prioritizating bridges for seismic retrofitting, and for post-earthquake response and recovery activities. More specifically, the areas that can benefit from the results of this task include the following:

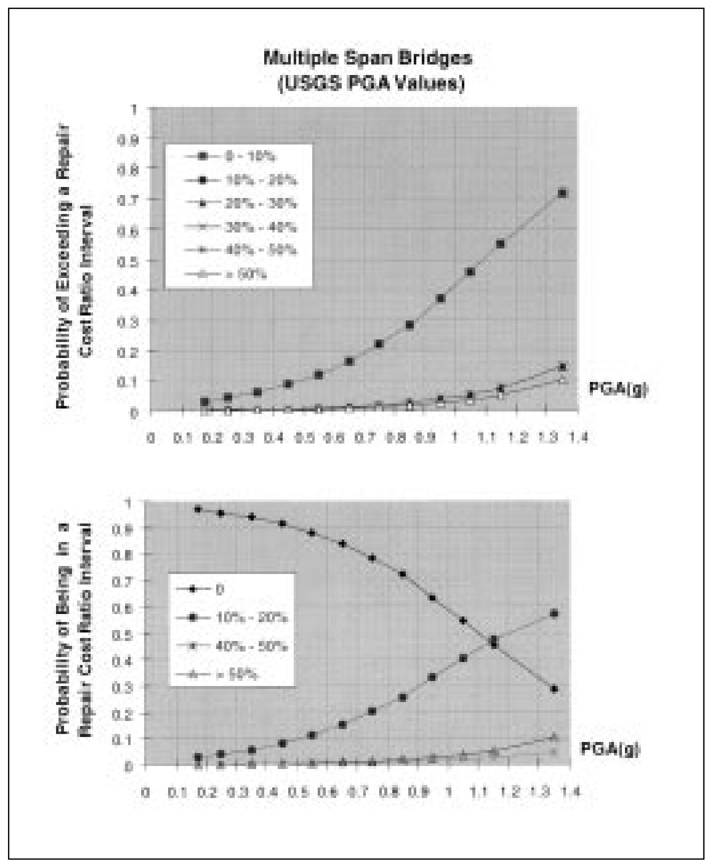

Figure 6: Empirical Fragility Curves for Multiple Span Bridges, Unconditional on Repair Cost Ratio

Database of bridge damage and structural characteristics: A comprehensive database will be available for the most recent two major earthquakes in the United States. This database includes information on bridge damage and the structural characteristics that are important for vulnerability assessment of bridges. This type of a database provides an essential base to improve our understanding of bridge damage from past earthquakes.

Classification of bridges and ground motion-damage relationships: Currently available bridge classes and the corresponding ground motion-damage relationships are rudimentary and do not properly estimate the observed damage from the Northridge earthquake. The method used in this research utilizes the observed damage data to develop empirical fragility curves which can and should be improved as more data become available. PGA levels, skew, span continuity, abutment type, and number of spans correlated well with observed damage. These are the characteristics used in the classification by Basöz and Kiremidjian (1996) and suggests that data shows good agreement with the structural characteristics used in that bridge classification.

Damage state definitions: Post-earthquake damage assessment is an important area that needs to be addressed for efficient and effective emergency response management. The damage states proposed in this research can be used to develop a post-earthquake investigation form that will assist in compiling bridge damage.

Repair cost-damage estimates: Repair cost ratio-ground motion relationships were developed for bridges grouped by various structural characteristics. The observed repair cost ratio for single span bridges was less than 10% while for multiple span bridges repair cost ratios as high as 50% were observed. The empirical repair cost-damage relationships and the repair cost ratio-ground motion relationships can be used to estimate the direct loss due to damage to bridges in earthquakes.

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Capacity Detailing of Columns, Walls and Piers for Ductility and Shear

by John B. Mander, Anindya Dutta and Chin Tung Cheng

This article presents research conducted under NCEER's Highway Project to develop seismic design and capacity detailing recommendations for bridge substructures. This paper describes work performed during the last two years. Comments and questions should be directed to John Mander, University at Buffalo, at (716) 645-2114 ext. 2418.

The objective of this research task is to develop seismic design and capacity detailing recommendations for bridge substructures. The emphasis is on the ductile detailing of the primary energy dissipating zones – the plastic hinges of bridge piers. Design equations for confinement are developed that would ensure sufficient plastic rotational capacity to avoid undesirable failure mechanisms; the final and unavoidable failure mode being low cycle fatigue of the longitudinal reinforcement.

Research Approach

The importance of lateral hoop reinforcement in improving the ductility level of circular columns is well known. Failure in a circular bridge column can arise from:

(a) Fatigue of the longitudinal reinforcing steel,
(b) Failure of the concrete due to either a lack of confinement or a fracture of the transverse hoops,
(c) Compression buckling of the longitudinal reinforcement.

Following the principles of capacity design, it is possible to avoid undesirable failure modes such as (b) and (c), leaving low cycle fatigue as the only unavoidable mode of failure. As a result, prediction of the amount of transverse reinforcement in the potential plastic hinge zones is of paramount importance to ensure "capacity protection" to the remainder of the structure. The first year of this two-year research effort therefore primarily focused on considering failure mode (a) fatigue of the longitudinal reinforcement. The second year has focused on failure modes (b) and (c) and thus methods of determining the appropriate quantity of transverse steel to "capacity protect" the structure. Early work by Mander et al. (1984, 1988a,b) led to an energy balance approach in which first hoop fracture of confined column sections could be predicted under concentric *axial compression*. This research extends that work by considering *cyclic flexure* in addition to axial compression. Thus design equations are developed for bridge columns for a range of cyclic demands.

Fatigue of Longitudinal Reinforcing Steel

Based on the experimental test results of recent studies by Mander et al. (1994) on the low cycle fatigue performance of reinforcing steels, it was shown that, regardless of the steel grade, a dependable plastic strain-life fatigue relationship is given by

$$\varepsilon_{ap} = 0.08(2N_f)^{-0.5} \tag{1}$$

where ε_{ap} = plastic strain amplitude and N_f = number of cycles to the appearance of the first fatigue crack.

By assuming a linear strain profile across the critical section of a concrete column, plastic strains can be related to the plastic curvature (ϕ_p) by

$$\phi_p = \frac{2\varepsilon_{ap}}{(D - 2d')} \tag{2}$$

where D = overall column diameter (or depth) and d' = depth from the outermost concrete fiber to the center of reinforcement (Note: D-$2d'$ = pitch circle diameter of the longitudinal steel in a circular column).

Substituting equation (2) into equation (1), one obtains a plastic curvature-life fatigue relationship for reinforced concrete columns

$$\phi_p D = \frac{0.113}{1 - 2d'/D} N_f^{-0.5} \tag{3}$$

where $\phi_p D$ = a dimensionless plastic curvature amplitude.

To validate equation (3), an experimental program was conducted on one-third scale model bridge column specimens. Eighteen column specimens have been tested to date in the experimental phase of this research. Eleven of them were tested under variable drift amplitude and seven column specimens were tested under constant drift amplitudes.

The experimental results relating fatigue life and plastic curvature are plotted in figure 1. Equation (3) is also plotted and it is evident that there is good agreement between the theory and observed experimental performance.

The following conclusions are drawn based on this research:

- Failure modes such as longitudinal bar buckling and transverse hoop fracture can be suppressed if sufficient transverse reinforcement is used. The failure mode thus becomes the low cycle fatigue *capacity* of the longitudinal reinforcement.
- The fatigue failure *capacity* of reinforced concrete bridge columns can be predicted by the theory presented herein without modification for low cycle fatigue failure mode.
- The concept of a renewable plastic hinge has been introduced and validated experimentally. The fatigue life *capacity* can be tuned to the fatigue *demand* by providing an appropriate length of fuse-bar and transverse confinement.
- Fuse-bars can easily be replaced after the column hinge zone has been damaged. The repaired column performs as well as the undamaged virgin columns.
- The performance of renewable hinge columns is insensitive to changes in the axial load and the aspect ratio.

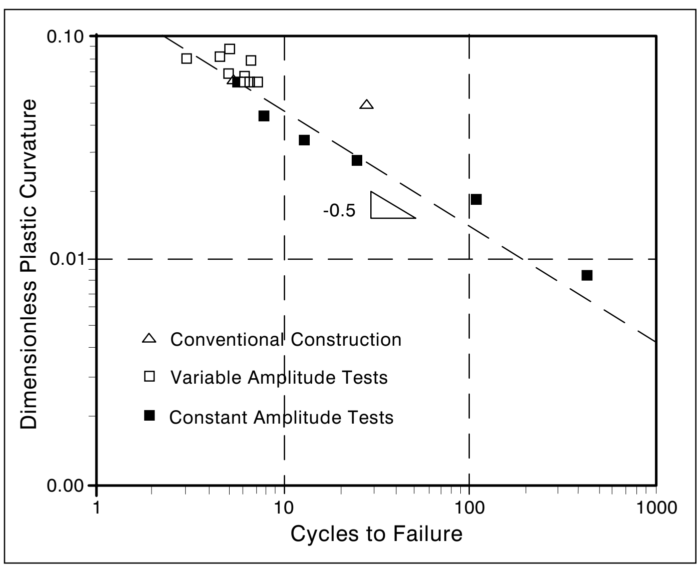

Figure 1: Relationship Between Dimensionless Plastic Curvature and Cycles to Failure

Energy Balance Theory for Confined Concrete

Based on the energy balance theory proposed by Mander et al. (1988a), the gain in ductility of a confined concrete member can be attributed to the energy stored in the transverse reinforcement. Using a virtual work approach in which the external work done on the section *(EWD)* is equal to the internal energy absorption capacity *(IWD)* of the section it is possible to write

$$EWD = IWD \qquad (4)$$

Internal work done on the critical section, that is the section's capacity to sustain plastic damage, is defined as the sum of the energy absorption capacity of the constituent materials: steel (U_{sh}) and concrete (U_{co}), thus

$$IWD = U_{sh} + U_{co} = \rho_s A_{cc} U_{sf} + A_g \int_0^{\varepsilon_{cu}} f_c \, d\varepsilon \qquad (5)$$

where ρ_s = volumetric ratio of the transverse reinforcement, A_{cc} = area of the core concrete and U_{sf} = area under the stress strain curve of steel reinforcement until fracture and according to Mander et al. (1988a) this may be taken as $U_{sf} = 110\ MJ/m^3$. Also in the absence of more rigorous analysis, the integral in the above expression which denotes the energy required to fail an equivalent unconfined column can be approximated as $0.008\ f'_c A_g$.

External work done results from the force actions of the neighboring concrete (U_{cc}) and longitudinal reinforcement (U_s) on the critical section. Consider the circular column section in figure 2. It is assumed that the available strain energy is consumed during cyclic loading by the concrete and the steel doing plastic work in cyclic compression. The plastic work done by the steel and the concrete is obtained by multiplying the forces in the compression steel and concrete by the appropriate plastic strain. Further, assuming that in a circular section, one-half of the total steel is lumped at both the ends of the pitch circle diameter and the rest is distributed in a thin rectangular strip of depth (*D" - d"*), the external work done can be expressed in terms of the sum of the plastic work done on each load reversal

$$\frac{U_s}{2N_c} = \left[0.25 + 0.5\frac{c''}{D''}\right] A_{st} f_y \frac{c''}{2D''} \frac{D''}{D} (\phi_p D) \qquad (6)$$

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and

$$\frac{U_{cc}}{2N_c} = \left[\eta_c + \frac{1-\eta_c}{N_c}\right] C_{cc}\frac{c''}{D''}(1-0.6\,\beta_c)\frac{D''}{D}(\phi_p D) \quad (7)$$

in which A_{st} = total longitudinal steel area, f_y = yield strength of the longitudinal steel, ϕ_p = plastic curvature, β_c = stress block depth factor and η_c = an efficiency factor to account for the reduced area of the concrete stress-strain curve after the first reversal. Note $2N_c$ denotes the total number of load reversals. Also C_{cc} = core concrete compression force which for circular sections can be shown to be equal to

$$C_{cc} = 1.32\alpha_c\left(\beta_c\frac{c''}{D''}\right)^{1.38} K f'_c\, A_{cc} \quad (8)$$

in which α_c = stress block factor is given by

$$\alpha_c = 0.667\left(1 + \rho_s\frac{f_{yh}}{f'_c}\right) \quad (9)$$

where f_{yh} = yield strength of the lateral reinforcement and ρ_s = volumetric ratio of that steel with respect to the core. This equation is based on a reanalysis of confined stress block parameters undertaken previously by Mander et al. (1984). The confined strength ratio K according to Mander et al. (1988a) is given by:

$$K = \frac{f'_{cc}}{f'_c} = -1.254 + 2.254\sqrt{1+7.94\frac{f'_l}{f'_{cc}}} - 2\frac{f'_l}{f'_{cc}} \quad (10)$$

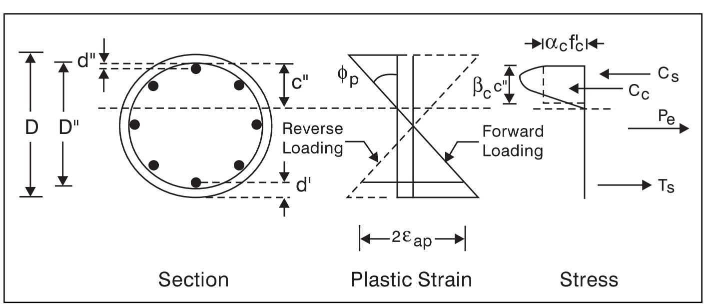

Figure 2: Core Concrete Parameters for Circular Column Sections

where f'_{cc} = peak stress of the confined core concrete and f'_l = effective confining stress provided by the transverse reinforcement at yield.

To simplify and reduce some nonlinearity in equation (7) simplifying assumptions are made. It is assumed that η_c = 0.33 and N_c = 4, thus the terms in square brackets equal *0.5*, and also β_c = 1.0. Note that the first term (*0.25*) in square brackets in equation (6) accounts for the fact that only half of the steel lumped at the extreme ends of the pitch circle diameter does work in compression.

Combining equations (6) and (7) and equating to equation (5), it is possible to obtain a fatigue-life equation in the form

$$(\phi_p D) = \Theta^{circ}_{hoop}\,(2N_f)^{-1} \quad (11)$$

where the fatigue-rotation coefficient

$$\Theta^{circ}_{hoop} = \frac{0.008 + \rho_s U_{sf} / f'_c}{\frac{c''}{4D''}\left\{\left[0.5+\left(\frac{c''}{D''}\right)\right]\frac{\rho_t f_y}{f'_c}\frac{D}{D''} + \alpha_c K\left(\frac{c''}{D''}\right)^{1.38}\frac{D''}{D}\right\}} \quad (12)$$

The neutral axis depth ratio (*c"/D"*) can be obtained from force equilibrium across the section. For a circular section it can be shown

$$\frac{c''}{D''} = \left(\frac{\frac{P_e}{f'_c A_g} + 0.5\rho_t\frac{f_y}{f'_c}\left(\frac{1-2c''/D''}{1-2d''/D''}\right)}{1.32\,\alpha_c K\frac{A_{cc}}{A_g}}\right)^{0.725} \quad (13)$$

It is possible to obtain an expression for the required volumetric steel ratio ρ_s. By using equation (3) to substitute for $\phi_p D$ in equation (11), it is possible to express the volumetric steel ratio in the form as

$$\rho_s = \frac{0.008 f'_c}{U_{sf}}\left[\Psi\sqrt{N_c} - 1\right] \quad (14)$$

where Ψ = factor which depends on section, hoop type and effectiveness. For circular sections, as an example,

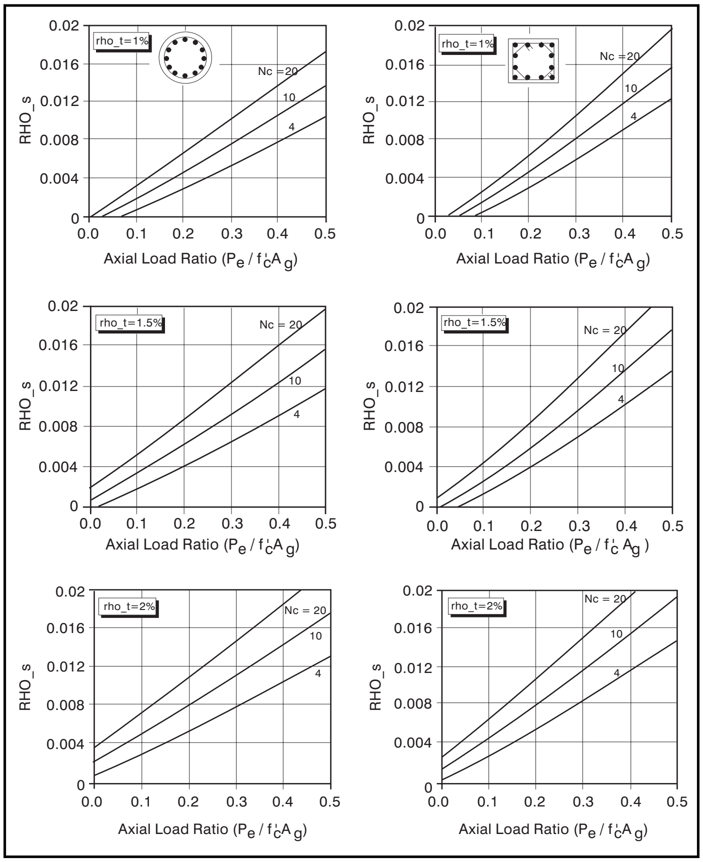

Figure 3: Design Charts for Column Sections

$$\Psi_{circ} = \frac{7D}{D''\text{-}2d''}\,\frac{c''}{D''}\,\frac{D''}{D}\left[\left(0.5+\frac{c''}{D''}\right)\frac{\rho_t f_y}{f_c'}\,\frac{A_g}{A_{cc}}+\alpha_c K\left(\frac{c''}{D''}\right)^{1.38}\right] \qquad (15)$$

Similar expressions can be obtained for rectangular sections as well. The results of the analysis for determining the transverse steel requirements (ρ_s) in terms of the axial load intensity ($P_e / f_c' A_g$), longitudinal steel volume (ρ_t) and cyclic loading demand (N_c) are presented in figure 3. Design curves are plotted for cyclic loading demands of 4, 10 and 20 cycles. These demands are based on recent work by Chang and Mander (1994) who found that for typical U.S. earthquakes, the equivalent number of constant amplitude cycles of loading is given by

$$N_c = 7T^{-1/3} \qquad (16)$$

but

$$4 \le N_c \le 20 \qquad (17)$$

where T = natural period of vibration of the structure. Equation (16) gives a cyclic demand spectra which is an implicit measure of earthquake duration effects.

Conclusion

The foregoing analysis provides a more rational basis for determining the transverse reinforcement required to prevent premature column failure. It considers the cyclic demand, the longitudinal steel volume and intensity of axial load – all factors that historically have been ignored in transverse steel design in the U.S.

Space does not permit the development of an energy-based analysis for determining the amount of transverse reinforcement necessary to prevent longitudinal bar buckling. This is another concern that is presently being investigated.

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Experimental Facilities

The RPI Geotechnical Centrifuge Facility

by Paul Van Laak, Ahmed-W. Elgamal, Thomas F. Zimmie and Korhan Adalier

The geotechnical centrifuge facility at RPI began operation in the summer of 1989 (see NCEER Bulletin, Vol. 3, No. 3, July 1989). This article summarizes much of the activity that has taken place in the facility from that time. For more information about the centrifuge facility, contact Professor Ricardo Dobry, Director of the Geotechnical Centrifuge Research Center, Rensselaer Polytechnic Institute, phone: (518) 276-6934; fax: (518) 276-4833; email: dobryr@rpi.edu or see the web page at www.rpi.edu/~gadrea/centrifuge.html.

In 1989, NCEER commissioned a geotechnical centrifuge facility at Rensselaer Polytechnic Institute in Troy, New York (RPI). Since then, it has been used in a number of research and engineering projects consisting of about three hundred tests and their interpretation and analysis, performed by dozens of researchers from both RPI and around the world.

The facility contains a 100 g-ton, medium sized centrifuge. The arm of the centrifuge has a total radius of 3 m, and the machine sits in a circular enclosure 7 m in diameter by 3 m in height (Elgamal, Dobry, Van Laak and Nicolas-Font, 1991). It is connected to the soil dynamics laboratory and other geotechnical experimental and computational research facilities occupying about 370 m^2 of floor space. This layout was designed to permit easy access and interaction between the centrifuge and the rest of the geotechnical research facilities. In addition, office space is provided for visiting researchers and other centrifuge users.

Equipment Development and Research

Since commissioning, there has been a continuous process of equipment and instrumentation development in addition to the research using the centrifuge. Initial projects have focused on failure mechanisms and seismic behavior of reinforced earth walls, liquefaction and lateral spread deformations due to earthquakes in both level and sloping terrain, seismic response and failure of shallow and deep foundations, as well as of retaining walls and earth embankments, comparison of soil improvement and stabilization technologies, static and dynamic friction of geosynthetics, evaluation of long-term performance of landfill construction materials, and modeling of groundwater and contaminant migration.

Equipment development has focused on the data acquisition system, video system for in-flight real time monitoring, equipment for construction of models, measurement transducers, and fabrication of a variety of model containers. In addition, several major equipment items have been developed. The ES-2.2 and ES-18 servo-hydraulic shakers, designed and fabricated at RPI, permit in-flight simulation of earthquake-induced shaking of centrifuge models (Van Laak, Elgamal, and Dobry, 1994a; and Van Laak, 1996). These devices are capable of delivering up to one ton (in the case of the ES-2.2) or up to nine tons (for the ES-18) of dynamic force to a centrifuge model while being spun at up to 100 g on the centrifuge. In order to provide appropriate model boundary conditions for dynamic tests, a flexible-walled laminar box model container, also developed at RPI, is used (Van Laak, Taboada, Dobry and Elgamal, 1994b).

Much of the equipment development and research summarized above has been supported by NCEER. This includes the construction of the ES-2.2 in-flight shaker and the laminar box container for realistic earthquake shaking simulations; and the studies of ground liquefaction and its effects on embankments and shallow and deep foundations, as well as centrifuge studies on the effectiveness of soil improvement measures proposed to mitigate these effects.

Cooperative Research Efforts

The activity of the RPI centrifuge has fostered national and international cooperation through contacts and common projects with investigators at other universities and research organizations. This has included centrifuge centers in the U.S. and abroad. Researchers and personnel from the following organizations have spent time at the RPI facility conducting their own model tests, collaborating with the RPI group or participating in centrifuge training courses: Brooklyn Polytechnic Institute, Czech Technical University of the Czech Republic, Hayward Baker Inc., Massachusetts Institute of Technology, National University of Mexico, Tokyo Institute of Technology, Tulane University, University of California/Los Angeles, University of Oklahoma, University of Southern California, University of Washington, and the U.S. Army Corps of Engineers Waterways Experiment Station.

Organizations that have contributed funds to the development of equipment or have sponsored research projects in the RPI geotechnical centrifuge facility include: Air Force Office of Scientific Research; Army Research Office; Bureau of Mines (Czech Republic); Clough Harbour Associates; Erving Paper Co.; Federal Highway Administration; General Electric Co.; Hayward Baker Inc.; International Paper Co.; Kajima Construction Co. (Japan); National Science Foundation; NCEER; INTEVEP (Venezuela); State of New York; U.S. Army Corps of Engineers Waterways Experiment Station; and U.S. Geological Survey.

Tables 1 and 2 summarize the research conducted and illustrate the variety of geotechnical, soil-structure interaction, and geo-environmental problems that have been studied through both static and dynamic model experiments. The first column of each table classifies the tests according to the engineering problem studied. The next column lists relevant publication(s), with the corresponding citation given in the list of references at the end of this article. Column three indicates the type of soil utilized in the project, and column four shows the type of engineering system under study. The next column lists the value or range of values of the centrifugal acceleration, N (g), at which the tests were carried out, and the last column shows the number of centrifuge model tests which produced results for that project.

Concluding Remarks

There is no doubt that, in conjunction with similar centrifuge studies done at other organizations, this research at RPI has considerably advanced our understanding of the response of soil and soil-foundation systems to earthquake shaking, especially at large deformations. Calibration of numerical models, development of better quantitative engineering evaluation procedures, and direct evaluation of ground improvement techniques have already started to impact the state-of-practice in earthquake engineering design of new structures and retrofitting of existing facilities. In addition to the specific contributions summarized above and those listed in the tables and corresponding references, NCEER's support for the RPI centrifuge facility and research has proven the usefulness of in-flight centrifuge modeling of earthquake shaking and earthquake forces acting on soil and soil-structure systems, as a very cost-effective and reliable new engineering tool.

Table 1: Summary of Centrifuge Tests from 1989 through August 1996 - Static Tests

Project Title	**References[1]**	**Soil Type**	**Classification[2]**	**N**	**No. of Tests**
Stability of braced excavations	Undergraduate research project (unpublished)	Medium sand	EX	80	2
Slope stability	Undergraduate research project (unpublished)	Medium sand	ES	100	2
Static response of mechanically stabilized earth walls	Ragheb & Elgamal (1991), Ragheb (1991)	Medium sand	ES, EX	39-83	13
Strength and stability of reinforced walls with geotextile reinforcement	Mahmud & Zimmie (1996, 1997) Mahmud (In preparation), Zimmie & Mahmud (1996)	Sand	ES, EX		10
Centrifuge modeling of radioactive waste migration in soil	De & Mahmud (1992), Mahmud (1993), Zimmie et al. (1993, 1994a, 1994e)	Clay	CTF	60	4
Long term performance of landfill cover materials	Zimmie et al. (1994b, 1994c)	Clay, Paper Sludge	CTF, LA	105	4
Total Static Tests					**35**

Notes:

[1] Complete citations are provided in the list of references.
[2] Classifications are abbreviated as follows: CTF: Contaminant Transport and Flow; DF: Deep Foundations; ES: Embankments and Slopes; EX: Excavations and Retaining Structures; LA: Landfills; LQ: Liquefaction and Lateral Spreading; SI: System Identification; SF: Shallow Foundations.

(Continued on Page 14)

Table 2: Summary of Centrifuge Tests from 1989 through August 1996 - Dynamic Tests

Project Title	References[1]	Soil Type	Classification[2]	N	No. of Tests
Dynamic testing of soil nailed excavations	Tufenkjian & Vucetic (1992), Tufenkjian et al., (1991)	Sand	EX	50	10
Seismic stability of reinforced earth walls	G. Anderson (Tulane, Texas A&M)	Sand	EX	50	15
Correlation of cone penetration data w/ earthquake induced lateral spreading	M. Sharp (In preparation)	Sand	LQ		9
Dynamic response of mechanically stabilized earth walls	Ragheb & Elgamal (1991), Ragheb (1991)	Medium Sand	EX		5
Seismic response of shallow foundations	Liu (1992), Liu & Dobry (1992), Dobry, Taboada & Liu (1995)	Fine Sand	LQ, SF	50	13
Application of vacuum surcharge for soil stabilization	Elgamal & Adalier (1996)	Sand	EX, LQ	40	14
Effect of overconsolidation on liquefaction resistance of sandy soils	Adalier (1996)	Sand	LQ	25	42
Metallic strip and geofabric reinforcement of level ground against seismic liquefaction	Adalier (1996)	Sand	LQ	40	14
Seismic response of dense and loose sand columns	Adalier (1996)	Sand	LQ	50	2
Aseismic stabilization of earth dams and slopes against soil liquefaction	Adalier (1996)	Sand, Clay	ES, LQ	40-75	19
VELACS: Experimental results of model #1	Taboada & Dobry (1993a)	Sand	LQ	50	2
VELACS: Experimental results of model #2	Taboada & Dobry (1993b), Dobry & Taboada (1994)	Sand	LQ	50	2
VELACS: Experimental results of model #3	Taboada & Dobry (1993c)	Sand	LQ	50	1
VELACS: Experimental results of model #4a	Taboada & Dobry (1993d)	Sand, Silt	LQ	50	2
VELACS: Experimental results of model #4b	Carnevale & Elgamal (1993a)	Sand, Silt	LQ	50	3
VELACS: Experimental results of model #7	Adalier & Elgamal (1993)	Sand, Silt	LQ	80	2
VELACS: Experimental results of model #10	Ting & Whitman (1993)	Sand	EX, LQ	50	18
VELACS: Experimental results of model #12	Carnevale & Elgamal (1993b)	Sand, Silt	LQ	100	3
VELACS2 tests: level ground	Adalier et al., (1997)	Sand	LQ	50	1
VELACS2 tests: embankment	Adalier et al., (1997)	Sand	LQ, ES	50	4
Effect of liquefaction on buried piles	Liu & Dobry (1995)	Fine Sand	DF, LQ	50	5
Lateral spreading	Taboada (1995), Dobry, Taboada & Liu (1995)	Fine Sand	ES, LQ, SI	50	10
Seismic response of landfills	Gunturi (1996)	Other	ES, LA	50	4
Seismic response of layered silty sand deposited under water	Dobry, Gutierrez & Zeghal (1996), M. Gutierrez (In preparation)	Silty Sand	LQ	40-100	15
Response of laterally loaded piles	A. Gadre (In preparation)	Sand	DF, SF		10
Effect of lateral spreading of layered sand deposit on pile foundation	T. Abdoun (In preparation), Abdoun et al. (1996)	Sand	ES, DF, LQ	50	13
Geosynthetic interface friction	Zimmie et al., (1994a,b,d), De, A. (1996), De & Zimmie (1997)	Other	ES, LA	5-60	5
Earthquake response of tilting retaining wall with saturated backfill	Ting & Whitman (1994)	Sand	EX, LQ	50	18
System identification	Zeghal & Elgamal (1994), Elgamal et al. (1996)		ES, LQ		—
Development of Laminar Box	Van Laak et al. (1994b)	Sand	LQ	50	2
Development of Earthquake Shakers	Van Laak, P. (1996), Van Laak et al. (1994a)	Sand	LQ	50-100	4
Total Dynamic Tests					**267**

[1,2] See notes under Table 1 for definitions.

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Center Activities

Staff News

NCEER's Deputy Director Accepts New Post

After serving for eight years as NCEER's deputy director, Dr. Ian Buckle has accepted the position of deputy vice chancellor for research and professor of civil engineering at the University of Auckland, New Zealand. As vice chancellor, Dr. Buckle, who is a leading expert in seismic isolation technology and an authority on the seismic performance of highway bridges, will be involved in shaping the direction of the research environment at Auckland, and will coordinate the various research programs in all disciplines at the University.

During his tenure at NCEER, Dr. Buckle oversaw several major accomplishments, including the renewal of the Center, and was instrumental in the development of the NCEER research program. Under his leadership, successful proposals to the Federal Highway Administration established the $14.2 million NCEER highway project which supports studies on the seismic vulnerability of highway systems and components, and which provides for the development of new technologies and design requirements. Dr. Buckle has also served as professor of civil engineering since 1989 at the University at Buffalo.

A native of New Zealand, Dr. Buckle received his bachelor's degree and Ph.D. at the University of Auckland, where he subsequently taught for 14 years. Dr. Buckle related that a senior administrative post in academia has long been one of his goals, a factor that initially attracted him to NCEER, which promised the chance to learn more about academic administration by working alongside the late Robert Ketter, former UB president, educator and administrator, who was the Center's first director.

In praising Dr. Buckle's leadership, dedication and direction at NCEER, Director George Lee remarked, "UB is losing a great faculty member, and the Center is losing a great deputy director, but it's a terrific opportunity for Dr. Buckle. This is a new beginning for him." Dr. Buckle will remain a member of the University at Buffalo faculty until the end of August. After August he will maintain academic ties as research professor at the University at Buffalo with involvement in the Center's highway research programs.

Workshop Review

Earthquake Engineering Frontiers in Transportation Facilities

by Jane Stoyle

The *NCEER-INCEDE Center-to-Center Workshop on Earthquake Engineering Frontiers in Transportation Facilities* was held March 10-11, 1997 in Buffalo, New York. The workshop was one of a series of joint meetings between U.S. and Japanese researchers involved in this cooperative project. During the first coordination meeting, participants from NCEER and INCEDE (International Center for Disaster Mitigation Engineering) met to develop a research agenda for the three year cooperative project. At that time, four focus areas of research were defined: water systems, power and gas; transportation; communication; and damage assessment. The focus of the March workshop was to share preliminary results from transportation-related projects with fellow collaborators. Over 30 participants from the U.S. and Japan attended the workshop.

The meeting began with a brief overview of the Japanese research agenda for the project by Dr. Tsuneo Katayama, Director General, National Research Institute for Earth Science and Disaster Prevention. Dr. George Lee, Director, NCEER, presented the corresponding U.S. agenda.

The ensuing discussions were structured around the technical areas of earthquake ground motions, soil behavior and response, underground structures, and the performance, analysis, design and reconstruction of highway bridges during and following damaging earthquakes.

NCEER's Director George Lee welcomes INCEDE's Director Ken Sudo to the Center-to-Center workshop on earthquake engineering frontiers in transportation facilities in Buffalo.

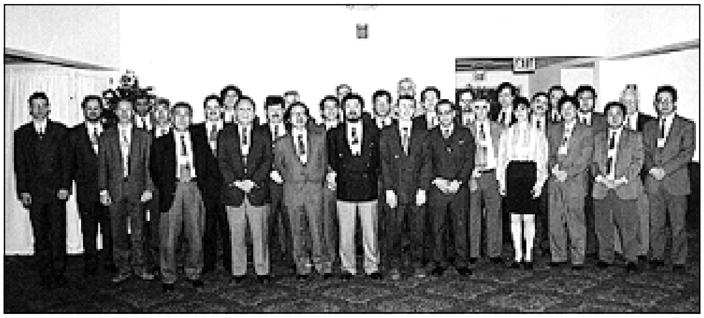
Participants suggested that increased cooperation between the U.S. and Japan under the structure of the Center-to-Center project would be beneficial to both countries for improving practice, policies, and procedures for preventing damage and for recovery following damaging earthquakes. As a result, the following resolutions were developed and approved during the workshop:

- There are many topics of common interest to the U.S. and Japan in earthquake damage mitigation and reconstruction of transportation facilities. It is therefore resolved that continued cooperation between researchers and practitioners in these two countries be encouraged, and mechanisms for improved technology transfer and sharing be explored.

- In view of the damage sustained to transportation facilities besides highways and bridges from recent earthquakes in California (Loma Prieta and Northridge) and Kobe, Japan, and the resulting impacts on traffic flow in these regions, it is resolved that future workshops held under Center-to-Center project sponsorship examine the operation of traffic management and control systems (hardware and software), and address issues related to identifying damage and performance of port and harbor facilities, and transit and railway structures, in order to assist in the development of improved mitigation and post-earthquake recovery strategies.

- Based on the above resolutions, it is further resolved that a second workshop on "Earthquake Engineering Frontiers in Transportation Facilities" be jointly organized by INCEDE and NCEER and held in Japan in approximately one year.

- Based on the results of this first workshop, opportunities for collaborative research and information sharing should be further explored, and potential funding sources for such collaborative research should be identified and contacted within the U.S. and Japan.



Participants at the Center-to-Center Workshop met to discuss research topics related to transportation facilities.

Proceedings from this workshop will be published by NCEER this summer. A specially-produced digital "sourcebook" is also planned. The sourcebook will be a compilation of information on disaster reconstruction lessons learned from both the Kobe and Northridge earthquakes. It will feature two page summaries that provide a brief description of the topic and references to more substantial sources of information. An advisory council will be established to oversee the development of the sourcebook.

Additional workshops in the remaining three thrust areas are being planned for later in the year. More information about INCEDE can be found on their web site, at *http://incede.iis.u-tokyo.ai.jp*.

PACE Course Review

Passive Energy Dissipation for Seismic/Wind Design and Retrofit

by Andrea Dargush

Instructors from the University at Buffalo and the University of California at Berkeley combined forces to offer the NCEER/EERC short course on *Passive Energy Dissipation for Seismic/Wind Design and Retrofit* in Irvine, California. The course was the third in a series of courses offered as part of NCEER's PACE (Professional and Continuing Education) program (see Vol. 10, No. 3, July 1996). Nearly 40 registrants participated in the three-day class, which was led by T.T Soong of the University at Buffalo and Andrew Whittaker of the University of California at Berkeley. Other instructors at the session, which was co-sponsored by the Los Angeles Department of Public Works Structural Engineering Division, were Michael Constantinou, Gary Dargush and John Mander of the University at Buffalo, and Ian Aiken of the University of California at Berkeley.

A focus of the Irvine course was a case study of the field implementation of passive energy dissipation technology in a U.S. Naval supply facility in San Diego, California. Following the course, a number of attendees took advantage of an optional post-course technical tour of the three-story, flat-slab building. Leading the tour were Matt Lysiak and Brian Cahill of Douglas, Barnhardt, Inc., which was responsible for the installation of the devices (others who participated in the retrofit were NCEER, 3M Company, and The Crosby Group). The completed retrofit illustrates the first seismic upgrade of a reinforced concrete structure using viscoelastic damper technology (see Vol. 11, No. 1, January 1997).

Over 100 structural engineers have already participated in the course, which has also been offered in Seattle and San Francisco. Future course offerings are being tentatively planned for this summer, at NCEER's facilities at the University at Buffalo and in Seoul, Korea and Tokyo, Japan. For more information on the PACE program, check NCEER's web site at *http://nceer.eng.buffalo.edu* or contact Andrea Dargush at NCEER, phone: (716) 645-3391; fax: (716) 645-3399 or email: *dargush@acsu.buffalo.edu*.

Participants took a post-course technical tour of a U.S. naval supply facility, which is the first RC structure to be retrofit with viscoelastic damper technology.

Seminar Series

The Department of Civil Engineering at the University at Buffalo and NCEER are jointly sponsoring a "Structural and Geotechnical Alumni Seminar Series" as part of the University at Buffalo's Engineering School's 50th anniversary celebration. The seminar series features alumni from the Civil Engineering Department, many of whom have participated in NCEER research projects. The seminars are held weekly on Friday afternoons on the University at Buffalo campus, and are coordinated by Professors Tsu T. Soong and Andrei Reinhorn. The first seminar was given by Professor Soong, who provided an overview of the series and the topics to be covered. Seminar reviews are written by graduate students in the school of engineering.

Stability of Elastomeric Seismic Isolation Bearings in Buildings

Presented by Satish Nagarajaiah
Reviewed by Joseph K. Quarshie

The stability of seismic isolation bearings was the subject of the seminar presented on March 7 by Dr. Satish Nagarajaiah, who is currently an assistant professor of civil engineering at the University of Missouri, Columbia. Dr. Nagarajaiah, a 1990 University at Buffalo alumni, is one of the developers of 3D-BASIS, a popular base isolation analysis and design software package developed at the department of civil engineering at the University at Buffalo. This seminar attracted 45 attendees including students and professors.

When isolation systems are used in structures, they introduce flexibility and thus increase the fundamental frequency of the structure. A base isolated structure therefore has a longer period than a fixed base structure. There are now provisions for base isolation in the uniform building code (UBC) as well as in the AASHTO bridge specifications.

Elastomeric bearings are just one of the isolation systems currently being used. They are laterally flexible due to their low shear stiffness. During a strong earthquake, larger lateral displacements and axial loads occur. These then cause P-delta effects in the bearings. It is therefore important to consider these effects when analyzing and designing the bearings due to concerns about stability under large displacements. This issue was the focus of the presentation.

Dr. Nagarajaiah cited previous works by other researchers such as Haringx (1948-49), Gent and Derham (1964), Buckle and Kelly (1986), Koh and Kelly (1986), and Buckle and Liu (1993 and 1994). He briefly explained each analytical model, including assumptions and limitations.

He then introduced a new analytical model, consisting of two rotational springs (one at the top and one at the bottom) and a lateral spring at the mid-height of the bearing. With all forces shown on the bearing, shear and rotational equilibrium equations for the system were derived.

Dr. Nagarajaiah showed various comparisons of the analytical and experimental results that were obtained on bearings of different sizes. Some of the charts displayed variations of critical load and horizontal displacement, shear-force horizontal displacement as a function of axial load, horizontal stiffness-horizontal displacement curves as a function of axial loads, and height reduction due to horizontal displacement as a function of axial load levels. Another set of comparisons showed experimental, analytical and ADINA results.

From these results, Dr. Nagarajaiah made the following conclusions: the critical load decreases with increasing horizontal displacement, unstable equilibrium paths past the limit point, and horizontal stiffness decreases with increasing axial load and horizontal displacement. In addition, for a given axial load, the shear force goes through a maximum as the horizontal displacement is increased and the tangential stiffness at maximum is zero. He also noted that the moment-horizontal displacement relationship increases with increasing axial load and goes through a maximum.

Finally, based on the good agreement shown in the comparisons between the analytical and experimental results, Dr. Nagarajaiah stated that the model may be reliably used to predict post critical behavior of elastomeric bearings of different sizes, shape factors, and rubber thickness.

The discussion that followed the presentation was brief. Essentially, clarification was sought on how a quasi-static model could effectively represent a real earthquake. It was agreed that calibration and verification of the model is based on some assumptions.

A Case Study of Seismic Vulnerability Assessment of Bridges

Presented by Genda Chen
Reviewed by Wilhelm Hammel

Continuing the civil engineering graduate seminar series, Dr. Genda Chen presented the sixth lecture on February 28. Dr. Chen, assistant professor of civil engineering at the University of Missouri-Rolla, presented *A Case Study of Seismic Vulnerability Assessment of Bridges*. Before joining the faculty at Missouri/Rolla in 1996, he worked as a senior engineer at Steinman, Parsons Transportation Group in New York. About 50 listeners, including faculty members and students from various departments, attended the seminar.

Dr. Chen's talk focused on the seismic hazard investigation of the Queensboro bridge in New York City. The bridge connects Manhattan and Queens and is a major link over the East River. About 174,000 vehicles use this bridge every day. The goal of the investigation was to decide whether to retrofit the bridge or to wait for an earthquake and then repair it.

First, Dr. Chen presented an overview of the design of the bridge, placing special emphasis on the structural details which affect seismic behavior. Information about the soil conditions and the seismicity of the area were also provided. He mentioned the occurrence of two magnitude 5.5 earthquakes in the past 100 years.

In contrast with previous seminars, Dr. Chen's presentation focused on a consulting engineering project rather than on pure academic research. He provided information about how a very complex project, involving far more than just a small engineering team, is conducted.

The general approach in this project was divided into several technical areas, such as the investigation of the ground motion parameters, including a response spectra for 500 and 2,500 year probability earthquakes; site effects, especially the local soil conditions; performing a seismic evaluation; computer modeling; and producing a cost evaluation.

The project team then synthesized the information gathered and provided a recommendation: that retrofitting the bridge would be approximately 20% of the cost of repairing it after the design earthquake occurred. To date, however, no formal decision has been made about retrofitting the bridge.

Dr. Chen concluded his talk with some future areas of research which will help to investigate these types of bridges in the future.

Efficiency of Nonlinear Controllers with Varied Actuators

Presented by Michael A. Riley
Reviewed by Rodolfo Garcia

On February 14, Dr. Michael A. Riley, research assistant professor of civil engineering at the University at Buffalo, presented a seminar titled *Efficiency of Nonlinear Controllers with Varied Actuators*. Dr. Riley received his Ph.D. from the University at Buffalo in 1996. His research specialties include structural control and experimental methods, and his work on active and hybrid controllers has included laboratory studies and full scale experimental implementation. Over 45 people, including faculty members and graduate students from a variety of departments, attended the fourth civil engineering seminar.

Dr. Riley presented a comparison between two classes of nonlinear control algorithms and their response effectiveness. They were both also compared with a classic simple linear controller. The responses of different control laws using the same controller and the responses of different controllers applied to the same structure were presented. The effectiveness and efficiency of control algorithms applied to specifically chosen controllers and structures were also shown during the presentation. The control algorithms considered were the third order optimal nonlinear controller and the modified bang-bang nonlinear controller. The classic simple linear LQR controller, also introduced, was only used for comparison purposes. The three algorithms were used to control two benchmark experimental model structures, one controlled by an active tendon system developed at the University at Buffalo and the other controlled by an active mass damper constructed at Notre Dame University. The responses produced by each of the nonlinear control laws with each controller were shown and compared with the uncontrolled responses as well as with the responses using the classic linear LQR controller.

Results from the benchmark study showed superior control was provided by the nonlinear controllers compared with the similar linear controller. Dr. Riley also noted that the variation in efficiency of nonlinear controllers was due to the type of control actuator used.

Following Dr. Riley's presentation, Dr. T.T. Soong, professor of civil engineering at the University at Buffalo and organizer of the seminar series, presented a brief talk describing the basic concepts for an active control system.

Predicting Inelastic Seismic Response of Structures: Modeling and Calibration

Presented by Sashi Kunnath
Reviewed by Paul Bradford

On Friday, February 21, Dr. Sashi Kunnath presented his lecture on *Predicting Inelastic Seismic Response of Structures: Modeling and Calibration* to a standing room only group consisting of students, professors, and practicing engineers. Dr. Kunnath, a 1989 University at Buffalo alumni, currently teaches at the University of Central Florida in Orlando where he is Director of the Graduate Program for the department of civil engineering. Recognized for his work in the area of numerical modeling of nonlinear hysteretic behavior, Dr. Kunnath is also one of the authors of the IDARC (Inelastic Damage Assessment of Reinforced Concrete) computer software.

Various modeling aspects of nonlinear structural analysis were presented, including an overview of the objectives of nonlinear analysis, global modeling, component and constitutive modeling, the importance of calibration and validation, modeling complexity, computational issues, as well as some final pieces of advice. Because of the subject breadth presented in Dr. Kunnath's fast paced lecture, topical depth was limited to salient points.

Modeling objectives were stated as:

- Accurate representation of structure stiffness and geometry
- Material modeling reflecting actual force-deformation behaviors
- Minimization of equilibrium errors and computational effort
- Post processing capabilities accurately depicting failure modes and damage distributions

Discussions related to global modeling included 2D and 3D model considerations, use of rigid vs. flexible elements, and approximating simplifications using SDOF representations. Dr. Kunnath stressed that understanding structure trends were germane to incorporating simplifications. An example was cited in which the expected mode shape for a framed structure may not match that of an SDOF cantilever idealization.

Component modeling included issues such as localized versus spread plasticity conditions, as seen in the yielding of steel and reinforced concrete members, respectively. Several different model types were discussed, all of which consisted of a linear elastic element in parallel with an inelastic element (plastic, elastic perfectly plastic, etc.). An additional level of accuracy, and complexity, can be added with the inclusion of different behaviors for positive and negative moments.

Important constitutive modeling issues included the consideration of performance versus material models. Material models include the explicit modeling of each material, while performance models are empirically based. In both cases, correlation between test results and computed results must be made. Case studies of component modeling were given as well. In one Cornell University study, test vs. computed component results correlated sufficiently such that when the various elements were superimposed (steel beam, RC column, and joint), global deformations matched.

Validation studies of IDARC included the juxtaposition of predicted damage to that experienced by a Holiday Inn structure (Van Nuys, CA). This seven story structure incurred damage in both the 1971 San Fernando and 1994 Northridge events. Instrumented at various floor levels for acceleration and displacement, ambient vibration analysis indicated an initial fundamental period of .58 seconds. Damage during the San Fernando event shifted this period from .70 seconds to 1.5 seconds during the initial and final phase of the shaking, respectively. After 25 seconds of shaking during the Northridge event, this period was shifted to 2.4 seconds. Analysis with IDARC showed good correlation with period lengthening due to inelastic damage.

The Van Nuys structure also provided insight into the applicability of the use of pushover type analyses in predicting seismic response. The static equivalent pushover methodology did not correctly identify damage locations, predicting inelastic damage only at the first story. Time history analysis, as verified by actual structure damage, correctly identified failure locations in the second through fifth stories.

Dr. Kunnath's concluding remarks included four recommendations: simplify when applicable, validate models, identify all modes of failure, and look for agreement in trends rather than mathematical exactness.

Active Control of Cable-Stayed Bridges

Presented by H. Allison Smith
Reviewed by Raul Barron-Corvera

Professor H. Allison Smith was the speaker for the seminar *Active Control of Cable-Stayed Bridges*. Held February 7, this was the third in a series of seminars presented at the University at Buffalo. Professor Smith is an assistant professor in the structures program of the civil engineering department at Stanford University. She received her B.S. degree in civil engineering from Clemson University in 1985 and her M.S. and Ph.D. degrees in structural mechanics from Duke University in 1987 and 1989. She is a recipient of both the NSF Presidential Young Investigator Award and the Office of Naval Research Young Investigator Award. Her primary research interests include structural control and computational dynamics.

An analytical model for active control of a cable-stayed bridge, based on the Jindo bridge located in South Korea, was presented. In modeling this bridge, some complexities were found, such as nonlinear behavior, multiple support excitation, and the participation of highly coupled high-order modes of vibration. In order to calibrate the analytical model, an experimental model for the bridge is being developed at the Colorado School of Mines.

The finite element model of the bridge has 316 degrees-of-freedom. Control algorithms required that the model size be significantly reduced. Among the reducer-order techniques investigated, modal superposition was superior to IRS and balanced reduction techniques. It yielded a small and accurate model suitable for control. The final control model includes 21 modes. LQR and H_∞ control algorithms were implemented with various actuator schemes to control both lateral and vertical excitations of the bridge deck. Various simulations were presented which showed how control effectiveness is highly sensitive to the modes participating on the overall bridge response. Results showed that control of cable-stayed bridges should emphasize reduction of internal bending moments instead of displacement as is done in buildings.

A discussion followed at the end of the seminar centered on topics such as: the feedback of internal moments into the control algorithms; the magnitude of the forces on the actuators; the time delay between the two support excitations and the possibility that anti-symmetric modes can be excited. Over 50 faculty and graduate students attended the seminar.

Numerical and Experimental Investigation of Vibration Screening by Trench Wave Barriers

Presented by Shahid Ahmad
Reviewed by Zhongyuan Zhu

On January 31, Dr. Shahid Ahmad presented *Numerical and Experimental Investigation of Vibration Screening by Trench Wave Barriers*. Dr. Ahmad is associate professor of civil engineering at the University at Buffalo. He has been a faculty member since January 1986, and a member of ASCE's soil dynamics committee since 1989.

Dr. Ahmad reviewed findings from numerical investigations on vibration screening effectiveness of open and infilled trench barriers conducted at the University at Buffalo. The vibration caused by operating machinery or traffic can cause discomfort to humans and structural damage to facilities. Therefore, it is sometimes necessary to reduce vibration. Surface waves can be reduced by placing a wave barrier between the source of vibration and the area to be protected. However, this method is not effective for body waves (i.e. the transmission direction is vertical). The terms active and passive protection are used to describe placement of the barriers. If the barrier is near the source, it is called active protection. If it is near the area to be protected, it is called passive protection. The criterion used for this kind of passive/active classification is different from that used to classify passive/active structural control.

In engineering practice, open and infilled trenches are often used as surface wave barriers to reduce ground vibration caused by surface waves of relatively small wave lengths. An open trench is empty (it only contains air, which is a good barrier for wave propagation). Infilled trenches use material such as concrete, soil-bentonite or geofoam. These infilled materials have different properties than the surrounding material (soil, sand, rock, etc.) to reduce wave propagation. In this presentation, Dr. Ahmad said that the depth of the trench has an optimum index (represented as D). Beyond this index, the effect of wave propagation reduction will not be improved significantly.

After reviewing the findings of a numerical investigation, the development of simple models in the form of algebraic expressions for estimating vibration screening effectiveness were discussed. These models were compared with Wood's (1968) field data and rigorous Boundary Element Method (BEM) solutions and acceptable agreement was found. Finally, findings from an experimental study on the influence of various geometrical and material parameters on vibration screening effectiveness of concrete and soil-bentonite trench barriers were discussed.

Center Resources

NCEER Technical Reports

Two New Reports Reviewed

NCEER technical reports are published to communicate specific research data and project results. Reports are written by NCEER-funded researchers, and provide information on a variety of fields of interest in earthquake engineering. The proceedings from conferences and workshops sponsored by NCEER are also published in this series. To order a report reviewed in this issue, fill out the order form and return to NCEER. To request a complete list of titles and prices, contact NCEER Publications, University at Buffalo, Red Jacket Quadrangle, Box 610025, Buffalo, New York 14261-0025, phone: (716) 645-3391; fax: (716) 645-3399; or email: *nceer@acsu.buffalo.edu*.

NCEER's world wide web site offers a complete list of technical reports and their abstracts. The publications section has recently been improved to allow users to search reports by subject, title, author and keywords. The order form has been integrated with the title listings, thus simplifying the order process. The web site address is *http://nceer.eng.buffalo.edu*.

Evaluation, Prevention and Mitigation of Pounding Effects in Building Structures
R.E. Valles and A.M. Reinhorn, 2/20/97, NCEER-97-0001, 280 pp., $20.00

Pounding between inelastic structures is investigated using an energy approach. A comprehensive state of the art review is first presented. The main characteristics of the pounding problem are identified and formulated in terms of energy. A Pseudo Energy Radius concept is introduced to study: 1) the minimum gap size to avoid pounding; 2) the amplifications due to pounding; and 3) the evaluation of different pounding mitigation techniques, including the use of supplemental damping devices and shock absorbers.

The formulations presented are then summarized to provide structural engineers with simple design/evaluation procedures to solve pounding problems. Building code considerations for pounding are also reviewed. Critical gap to avoid pounding is usually specified in terms of the sum of the maximum displacements, or as a percentage of the height, or as a fixed quantity, or as a SRSS combination of the response. Making use of the improved correlation coefficient based on the above mentioned Pseudo Energy Radius, the Double Difference Combination rule may be used to calculate the critical gap to avoid pounding. The formulation can be extended to determine more rational critical gap formulations in seismic codes.

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Proceedings of the U.S.-Italian Workshop on Seismic Evaluation and Retrofit
Edited by D.P. Abrams and G.M. Calvi, 3/19/97, NCEER-97-0003, 266 pp., $20.00

These proceedings represent the second time NCEER and their counterparts, the National Group for the Defense against Earthquakes (GNDT) of the Italian National Research Council, have convened workshops as part of a Memorandum of Understanding. The workshop was held in December 1996 in the U.S. on seismic evaluation and retrofit of buildings and bridges. The invited workshop papers focused on general issues for discussion including: how research has been used to change practice; what problems need to be solved for the next generation of codes; and what research needs may emerge in the next decade through technology advancements. Discussions at the workshop resulted in a series of resolutions that are included in the proceedings.

News from the Information Service

by Dorothy Tao

New Search Engine for Quakeline

Beginning April 1, 1997 the Quakeline® database will be searchable through Glimpse/HTTP® software mounted on the NCEER web site (*http://nceer.eng. buffalo.edu*). Telnet access to Quakeline® through the University at Buffalo's BISON Information System will be eliminated due to the University at Buffalo Libraries' move to a world wide web-based version of BISON.

Developed by Udi Mander, Paul Klark, and Michael Smith of the University of Arizona Computer Science Department, Glimpse/HTTP software will run Quakeline and will eventually be used to index other areas of the NCEER web site. Some significant new features offered by Glimpse/HTTP include the ability to use boolean ("and," "or," "not") and phrase searching to formulate search statements, the highlighting of search terms within the context of the ability to use boolean ("and," "or," "not") and phrase searching to formulate search statements, the highlighting of search terms within the context of the records, and the ability to download groups of records through the use of a "tagging button." Access to the database is through the Quakeline "hot link" at the bottom of the opening screen of the NCEER web site or through the Information Assistance section of the NCEER web site. Comments and suggestions are encouraged and should be directed to Carol A. Kizis, Quakeline Database Coordinator, phone: (716) 645-3377; fax: (716) 645-3379; or email at *cakizis@acsu.buffalo.edu*.

Creating and Maintaining the Upcoming Meetings List

To inform the earthquake engineering community of activities that may be of professional interest, a list of upcoming meetings is published in each issue of the **NCEER Information Service News**. (The **News** is also available on NCEER's web site at *http://nceer.eng.buffalo.edu*). Users and conference planners often contact the Information Service to inquire about details for specific meetings, how the list is compiled, the scope of the materials and how to submit items to the list.

For the most part, the events in the "Meetings" list are culled from press releases and announcements that are mailed or faxed to the Information Service, as well as calendars and "upcoming events," from the hundreds of journals and newsletters that are received each month. These materials are scanned for meetings of interest to readers, and checked to see if a meeting has been previously listed.

If a meeting was not previously listed, it is included in the current month's **News**. Each listing contains the name of the meeting, date, location, contact person, as well as telephone, fax, e-mail and if available, web site address. While the "Meetings" list is proofread and documentation is filed for each listing, because of time constraints, the information provided for each meeting is not verified unless there is an obvious conflict between two sources of information. Therefore, readers are cautioned not to consider the "Meetings" list the definitive source of information about a particular event. Because secondary sources are used, those planning conferences and making travel reservations should verify information by contacting the conference organizers directly.

Space constraints prevent the printing of a complete list of meetings every month, and only newly announced (or those that have had a change of venue) activities appear in monthly issues. A complete listing of all known meetings can be found on the Internet by gopher or ftp to *nceer.eng.buffalo.edu* or the web site at *http://nceer.eng.buffalo.edu*. A useful feature of the web version of the "Meetings" list is that it is interactive. For example, if an e-mail or web site address is included for any meeting, a hot link to that address is provided, so users can immediately send a request or comment to the contact. Other organizations may wish to supplement their own web listings by linking to this very comprehensive compilation. The NCEER Information Service solicits help from readers in keeping the "Meetings" list current by asking that conference and meeting information be sent to the Acting **News** Editor, Dorothy Tao, phone: (716) 645-3377; fax: (716) 645-3379; or email at *singtao@acsu.buffalo.edu*.

Bulletin Board

Upcoming Events

Third International Conference - Local Authorities Confronting Disasters and Emergencies

The *Third International Conference - Local Authorities Confronting Disasters and Emergencies* will be held June 26-July 1, 1998 in Edmonton, Alberta, Canada. For more information, visit the conference's web site at *http://www.freenet.edmonton.ab.ca/disaster* or email directly to: Herb Presley, Disaster Services Officer, Alberta Transportation and Utilities, email: *preslh@censsw.gov.ab.ca*.

Innovations in Structural Design: Strength, Stability, Reliability

The Symposium on *Innovations in Structural Design: Strength, Stability, Reliability* will be held June 6-7, 1997 in Minneapolis, Minnesota. The symposium is being held in honor of Professor Ted Galambos, who recently retired from the University of Minnesota. For more information, contact Susan Potratz-Johnson, Professional Development and Conference Services, 214 Nolte Center, 315 Pillsbury Dr., S.E., Minneapolis, MN 55455; phone: (612) 625-5886; email: *spotratz@mail.cee.umn.edu.*

1997 American Control Conference

The *1997 American Control Conference* will be held in Albuquerque, New Mexico on June 4-6, 1997 with workshops on June 2, 3 and 7. For more information, visit the conference web site at: *http://www.eece.unm.edu.us/controls/ACC97* or contact General Chair, Naim A. Kheir, phone: (810) 370-2177; fax: (810) 370-4633; email: *kheir@vela.acs.oakland.edu.us*; Registration Chair, M. Edwin Sawan, phone: (316) 978-3415; fax: (316) 978-3853; email: *ed@shocker.ee.twsu.edu.us*; Workshop Chair, Michael K. Masten, phone: (972) 995-7986; fax: (972) 927-4168; email: *m.masten@ieee.org.us*.

Seismic Design Practice into the Next Century - Research and Application

The Sixth Society for Earthquake and Civil Engineering Dynamics (SECED) Conference on *Seismic Design Practice into the Next Century - Research and Application* will take place March 26-27, 1998 at the University of Oxford, U.K. For more information, contact Rachel Coninx, Thomas Telford Conferences, Institution of Civil Engineers, One Great George Street, London, SW1P 3AA, UK, phone: (+44) (0) 171-665-2314; fax: (+44) (0) 171-233-1743; email: *coninx_r@ice.org.uk* or visit the web site at *http://www.t-telford.co.uk/co/conflist.html*.

Call For Papers

1997 Meeting, Eastern Section - SSA

The *69th Annual Meeting of the Eastern Section of the Seismological Society of America* will be held October 5-8, 1997 in Ottawa, Canada. Papers dealing with seismicity, tectonics, seismic hazards, real-time seismology, earthquake source studies, ground motion, and earthquake engineering are invited. For more information, contact Gail Atkinson, phone: (613) 520-2600 ext. 1399; email: *esssa@ccs.carleton.ca* or visit the web site at *http://www.seismo.nrcan.gc.ca/esssa97*. Abstracts are due by August 29, 1997.

Northridge Earthquake Research Conference

The *Northridge Earthquake Research Conference* will be held August 20-22, 1997 in Los Angeles, California. The conference will highlight results obtained in research projects in many disciplines, including earth science, engineering, and social science and emergency management. Papers which summarize research findings are invited. For more information, contact Northridge Earthquake Research Conference, California Universities for Research in Earthquake Engineering, 1301 South 46th St., Richmond, CA 94804; phone: (510) 231-9557; fax: (510) 231-5664; email: *curee@nisee.ce.berkeley.edu*. Abstracts are due May 2, 1997.

Long-Span and High-Rise Structures

The International Association for Bridge and Structural Engineering is sponsoring the *Long-Span and High-Rise Structures - Engineering Challenges for the 21st Century* symposium, to be held September 2-4, 1998 in Kobe, Japan. Papers dealing with design issues, structures and their environments, caring for structures, and case studies are invited. For more information, contact: Symposium Secretariat, IABSE, ETH Hönggerberg, CH-8093, Zurich, Switzerland, phone: (+41) 1-633-2647; fax: (+41) 1-371-2131; email: *secretariat@iabse.ethz.ch* or visit the web site at *http://www.iabse.ethz.ch*. Abstracts are due June 15, 1997.

1997 SEAOC Annual Convention: Practical Based Design

The Structural Engineers Association of California will hold its 1997 Annual Convention in San Diego, California on September 25-27, 1997. Papers on structural analysis, design, construction and rehabilitation of building structures, bridges, and other structures are invited. For more information, contact Craig Rush, 1997 SEAOC Convention, R2H Engineering, Inc., 11545 W. Bernardo Ct., Suite 300, San Diego, CA 92127; phone: (619) 673-8416; fax: (619) 673-8418. Abstracts are due May 15, 1997.

NSF Implements New Merit Review Criteria

Last year the National Science Foundation and the National Science Board formed a Task Force to suggest changes to NSF's merit review criteria, which had not been revised since 1981. The Task Force unveiled its proposed criteria in November 1996 (see FYIs #162 and #163, 1996) and made them available to the scientific and engineering communities for public comment. Based on the 325 responses received over a two-month period, the Task Force revised its draft criteria and presented them to the NSB at its March 27-28, 1997 meeting. The Board approved the new criteria and authorized NSF Director Neal Lane to "proceed expeditiously with all steps necessary" to implement them for all proposals reviewed beginning October 1, 1997.

The Task Force reduced the number of criteria reviewers must consider from four to two. Each of the criteria has a set of related questions to help reviewers evaluate the proposals. The instructions make clear that the two criteria "need not be weighted equally." Reviewers are asked to provide separate comments for each criterion, a single composite rating of the proposal, and a summary recommendation that addresses both criteria.

Based on the public comments, the Task Force altered its proposed criteria and associated questions to place more emphasis on researcher competence, and to clarify wording on issues of diversity, creativity, benefits to society, and management of the research plan. Some questions were rephrased to encourage reviewers to provide explanations rather than yes-no answers. The Task Force believes that "adoption of the new criteria will facilitate, clarify and simplify the proposal evaluation process." The revised criteria, as approved by the National Science Board, are quoted as follows:

1. What is the intellectual merit of the proposed activity?

The following are suggested questions to consider in assessing how well the proposal meets this criterion: How important is the proposed activity to advancing knowledge and understanding within its own field and across different fields? How well qualified is the proposer (individual or team) to conduct the project? (If appropriate, please comment on the quality of prior work.) To what extent does the proposed activity suggest and explore creative and original concepts? How well conceived and organized is the proposed activity? Is there sufficient access to resources?

2. What are the broader impacts of the proposed activity?

The following are suggested questions to consider in assessing how well the proposal meets this criterion: How well does the activity advance discovery and understanding while promoting teaching, training, and learning? How well does the proposed activity broaden the participation of underrepresented groups (e.g., gender, ethnicity, geographic, etc.)? To what extent will it enhance the infrastructure for research and education, such as facilities, instrumentation, networks, and partnerships? Will the results be disseminated broadly to enhance scientific and technological understanding? What may be the benefits of the proposed activity to society?

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