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16. ABSTRACT

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Office of Geotechnical Engineering

Minor Research Report

SYNTHESIS OF CALTRANS' FOUNDATION SEISMIC RESEARCH PROGRAM

November 2, 1992

Research Expenditure Authorization 638041-33166
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CALTRANS' FOUNDATION SEISMIC RESEARCH PROGRAM

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ABSTRACT: An overview of the Caltrans-sponsored research program focused on the seismic performance of substructures is presented. A current listing of projects sponsored by each of two Divisions is tabulated. Selected projects related to ground-motion prediction and foundation performance are discussed individually.

1. Introduction

In response to the recommendations of the Governor's Board of Inquiry into the Loma Prieta Earthquake of 1989, Caltrans initiated a comprehensive research effort to examine various aspects of the seismic behavior of bridge structures. A large proportion of this work is administered by the Division of Structures (DOS) which has reviewed more than 130 research proposals, and let more than 40 contracts worth in excess of $8 million to both public and private organizations. This research is supported with both special state (SB-36) funds as well as conventional federally-matched highway research (SP&R) allocations. The DOS seismic research program focuses on all aspects of seismic bridge design including subsurface considerations such as regional and local seismicity, ground response characterization, and substructure performance. For information on the broader structural-related seismic research sponsored by DOS, the reader is directed to the following references {1,2,3}.

The Division of New Technology, Materials and Research (DNTMR) within Caltrans provides both internal-staff studies and external-contract research on a wide variety of transportation-related topics while providing numerous specialty services to both DOS and Caltrans Districts. The Offices of Geotechnical Engineering and Engineering Geology within DNTMR routinely provide both site-specific ground response analyses and subsurface characterization information, respectively, to DOS. Seismic research administered by DNTMR is complementary to the larger DOS program, and is funded exclusively through SP&R allocations. The seismic research performed by DNTMR is focused primarily on subsurface considerations including site and material characterization, ground response analysis, and field load testing of foundations.

This paper is intended to provide a current overview of the seismic foundation-related research program sponsored by Caltrans. The overall scope of the program is reflected in Table 1 which provides a listing of the current projects administered by both DOS and DNTMR along with the project identification, Caltrans manager, principal investigators, research organization, current status, and

#	Project	Project Type/ID/ Contract or EA	Manager/ Division	Investigators/ Organization	Status/ Term	Approx. Budget
Performance During Loma Prieta						
1	Evaluation of Dumbarton Bridge Response in the Loma Prieta Earthquake.	Contract w/ UCB ID: S91SD86 RTA 59N206	Sheng @ DOS	Fenves @ UC-Berk	100% Complete 5/90 - 6/91	$50,000
2	Phase 1: Inspection and Data Collection on the Substructure of the Bay Bridge. Phase 2: Seismic Condition Assessment of the Bay Bridge.	Contract w/ UCB Ph1 ID: F90SD23 Ph1 RTA 59NO62 Ph2 ID: S91SD88 Ph2 RTA 59N580	Sheng @ DOS	Astaneh, Bolt, Lysmer, Powell, Fenves, Mosmiro, Stephen @ UC-Berk	90% Complete 1/90 - 12/92 50% Complete 1/90 - 6/93	$50,000 $637,000
Seismic Response Studies						
3	Seismic Evaluation of Northern California Bridge Sites.	Consultant Contract # 59N772	Wilhelms @ DNTMR	Powers @ Geomatrix	75% Complete 11/91 - 3/93	$900,000
4	Seismic Evaluation of Southern California Bridge Sites.	Consultant Contract # 59N771	Mualchin @ DOS	Moriwaki @ Woodward-Clyde in Santa Anna	50% Complete 2/92 - 12/92	$371,000
5	Multiple-Support Response Spectrum Analysis of Bridges.	Contract w/ UCB ID: not assigned	Kirkland @ DOS	Der Kiureghian @ UC-Berk	0% Complete 1/93 - 6/94	$94,000
6	Seismic Analysis of the San Francisco-Oakland Bay Bridge	Contract w/UESC ID: S91SD87 RTA: 59N616		Duggan @ GENSYS/UESC	In Contract Execution	$170,000
Ground-Motion Prediction						
7	Seismic Response of Deep Soil Sites in the San Francisco Bay Area.	Contract w/ UCB ID: S91SD85 RTA 59N224	Mualchin @ DOS	Seed, Lysmer @ UC-Berk.	80% Complete 7/90 - 6/93	$315,000
8	Comparison of Geophysical Methods for In Situ Velocity Measurement - Islais Site.	Internal Minor ID: F92RM01 EA: 638005-32138		Roblee @ DNTMR	60% Complete 2/92 - 12/92	$13,000
9	Examination of the Impact of Updated Soil Models on Caltrans Standard ARS.	Internal Minor ID: F93RM01 EA: 638041-33152		Shantz, Roblee @ DNTMR	25% Complete 8/92 - 1/93	$10,000
10	Response of Soil Sites During Strong Seismic Shaking.	Contract w/ UCD ID: F92SD29 RTA 59T342	Moese @ DOS	Idriss, Kutter, Li @ UC-Davis	10% Complete 8/92 - 8/93	$125,000
11	Development of a Prototype Tool for In Situ Determination of High-Strain Dynamic Properties of Soft to Medium-Stiff Clays.	Contract w/ UCD ID: F92TL05 RTA: 65T324	Roblee, Jackura @ DNTMR	Li, Idriss, Herrmann @ UC-Davis Chan @ UC-Berk.	5% Complete 8/92 - 6/95	$709,000
12	Review of Soil Amplification Provisions in Current World-Wide Seismic Design Codes.	Internal Minor ID: F93RM01 EA: 638041-33151		Shantz, Roblee @ DNTMR	5% Complete 9/92 - 3/93	$10,000
13	Evaluation of Non-linear Seismic Site Response Models.	Contract/Internal ID: F92TL13	Roblee @ DNTMR		In Proposal	$70,000
14	Strong-Motion Instrumentation of Subsurface Profiles.	Contract ID: F92TL14	Roblee @ DNTMR		In Proposal	$230,000
Soil-Structure Interaction						
15	Improved Mathematical Idealizations to Include Foundation Effects on the Seismic Response of Highway Bridges.	Contract w/ UCB ID: F78SD15 RTA 59F453	Gates @ DOS	Penzien @ UC-Berk Imbsen @ Imbsen & Assoc.	100% Complete 7/81 - 90	$398,000
16	Parametric Studies for the Seismic Modeling of Two-Level Elevated Freeways: Work Package 11.	Contract w/ Cygna		Ghose @ Cygna Group	100% Complete 11/89 - 6/91	
17	Implementation of Advanced Soil-Structure Interaction Techniques for Analysis of Bridge Structures.	Contract w/ C. A. ID: S92SD13 RTA 59S035	Mitchell @ DOS	Sweet @ Coast Analytics	30% Complete 4/92 - 4/93	$82,000
18	Development and Evaluation of Dynamic Soil-Pile Interaction Models, Phase I.	Internal Minor ID: F93RM01 EA: 638041-33155		Slyh, Jackura @ DNTMR	20% Complete 9/92 - 12/92	$10,000
19	Development & Implementation of Impr. Seismic Design and Retrofit Procedures for Bridge Abutments.	Contract w/ USC ID: not assigned		Martin @ USC	In Contract Execution	$122,000
20	Pile Survivability and Soil-Pile Interaction.	Internal Minor ID: F93RM01 EA: 638041-331xx		Slyh, Jackura @ DNTMR	In Proposal 10/92 - 3/93	$10,000
Review of Design Procedures						
21	ATC-32 Review and Revise Standards, Performance Criteria, Specifications and Practices for the Design of New Bridge Structures and Rehab of Existing Structures.	Contract w/ ATC ID: S92SD11 RTA 59N203	Sultan @ DOS	Rojahn, Nutt @ Applied Technology Council	40% Complete 8/91 - 12/93	$555,000
22	Study of Caltrans' Seismic Evaluation Procedures for Short Bridge Overcrossing Structures.	Contract w/ D&M ID: S92SD15 RTA 59Q122	Huang @ DOS	Werner @ Dames & Moore	10% Complete 8/92 - 7/93	$312,000
Structural Aspects of Substructures						
23	Experimental Testing of Epoxy-Injected Steel Shell Retrofitted Sections from the Collapsed Struve Slough Bridge - Phase 1 and 2.	Contract w/ UCD ID-Ph1: S91SD82 ID-Ph2: F92SD28 RTA-Ph1: 59N204 RTA-Ph2: 59S814	Travis @ DOS	Ramey, Romstad @ UCD	50% Complete 1/90 - 7/93	$100,000
24	Seismic Retrofit of Bridge Column Footings.	Contract w/ UCSD ID: F91SD80 RTA 59M494	Mitchell @ DOS	Priestley, Seible @ UC-San Diego	25% Complete 10/91 - 6/93	$375,000
Field Load Tests						
25	Lateral Load Tests on Driven Pile Footings at Cypress Viaduct.	Demolition Contract w/ Christie Const.	Jensen @ DOS	Abcarius @ DOS	100% Complete 11/89 - 2/90	~$45,000
26	Full-Scale Medium-Level Vibration Test at Meloland Road Overcrossing.	Contract w/ UNR ID: F88SD16 RTA 59G454	Klein @ DOS	Douglas @ UN-Reno	90% Complete 1/88 - 2/93	$375,000
27	Full-Scale Lateral Load Test of Large-Diameter Drilled Shafts Founded in Fractured Rock.	Design-Phase Contract for DOS EA: 04-191794	Seaberg @ DOS	Speer @ DNTMR	75% Complete 10/91 - 12/92	$300,000
28	Experimental Measurement of Bridge Abutment Behavior: Stiffness, and Ultimate Strength Characteristics.	Contract w/ UCD ID: S92SD10 RTA 59Q183	Moese @ DOS	Romstad, Kutter @ UCD Maroney @ DOS	50% Complete 4/91 - 9/93	$423,000
29	Tension and Compression Testing of 9 Pile Types in Bay Muds Underlain By a Firm Stratum.	Construction-Phase Contract for DOS EA: 04-191794	Mason @ DOS	Speer, Morris @ DNTMR Mason @ DOS	50% Complete 11/91 - 6/93	$750,000

Table 1. Summary of current Caltrans-sponsored seismic foundation research projects.

total budget for each project. Note that both the status and budget figures appearing in Table 1 are approximate. For purposes of providing a framework for discussion, the projects have been grouped into broad categories such as "ground motion prediction". It should be recognized that many projects overlap into several of these categories. Within a particular grouping, the projects are listed in descending order according to the approximate completion status.

The remainder of this paper will provide both a brief review of the general objectives of each project listed in Table 1, as well as a more detailed discussion and some preliminary findings from selected projects for which the author has greater familiarity. In-depth results are beyond the scope of this paper, therefore, the reader is encouraged to contact the appropriate project manager listed in Table 1 for additional information and/or reports pertaining to specific topics of interest. To facilitate project identification in the remainder of the text, numbers appearing in square brackets (e.g. [1]) will denote the project number appearing to the extreme left in Table 1.

2. Performance During Loma Prieta [1, 2]

Shortly after the Loma Prieta earthquake of 1989, research contracts were let by Caltrans DOS to perform preliminary investigations on each of two long multi-span Bay Area bridges. First, the dynamic response of the Dumbarton Bridge was examined because of the extensive data set which was collected during the event by a network of 24 strong-motion accelerometers installed on the structure. Second, documentation of damage sustained by the East Crossing of the Bay Bridge was collected. Detailed presentations on each of these projects can be found elsewhere, therefore, discussion herein will be brief.

The data recorded at the Dumbarton Bridge provides a unique case history of the seismic response of a long structure which is partially founded within deep soft clay. Records from the Loma Prieta event indicate that significant soil amplification effects occurred, and that over 60 seconds of strong bridge response were caused by approximately 30 seconds of free-field input motion. Fenves et al [1] {4, 5, 6} of the University of California at Berkeley (UCB) analyzed the dynamic response of the bridge-foundation-soil system using a linear elastic model having 6500 elements and 12,600 degrees of freedom. Embedded portions of substructure components were modeled with translational and rotational springs according to a method developed by Novak. Free-field ground motion was prescribed at the foundation elements using a combination of recorded and calculated displacement histories which varied along the length of the bridge. Analysis results indicate excellent correlation with recorded mode periods, and reasonable correlation with recorded displacement histories. These investigators conclude that bridge response modeling is very sensitive to both the varying input motion specified along the length of the bridge, and to assumptions regarding modeling of the foundations. An additional investigation into the seismic response of the Dumbarton Bridge has been proposed by Heuze of LLNL, and will take advantage of supplemental subsurface information which Caltrans is currently acquiring.

The unsatisfactory performance of the East Crossing of the Bay Bridge during the Loma Prieta event focused intense scrutiny on the anticipated structural behavior of this system during future events. Shortly after the earthquake, both Caltrans and NSF provided funds to Astaneh [2, phase 1] of UCB to perform preliminary research which focused on a detailed documentation of the "perishable data" pertaining to damage sustained by the structure. These and other results were compiled into the Governor's Report {7} which concluded that there was no evidence of foundation failure in terms of settlement, displacement, or loss of bearing capacity. However, it also states that soil-structure interaction at the piers may have influenced the dynamic response of the bridge. A comprehensive state-of-the-art seismic assessment of the Bay Bridge is currently underway by a group of UCB researchers under the general direction of Astaneh [2, phase 2] {8, 9}.

3. Seismic Response Studies [3, 4, 5, 6, 7]

Several investigations are underway which focus on various aspects of the seismic response of certain Caltrans structures. The studies identified in this and the following section on "ground motion prediction" are closely related. However, the investigations discussed here are primarily from the perspective of the seismologist, while those presented in the following section are oriented toward the geotechnical engineering perspective.

Two separate investigations are underway to characterize local seismicity in terms of both deterministic and probabilistic analyses for specific major bridge sites in northern and southern California. Although these projects are not part of the official research program of Caltrans, both investigations represent current state-of-the-art assessments, and are viewed as contributing to the overall seismic research goals of Caltrans. Geomatrix [3] was selected to perform seismic evaluations for Northern California bridge sites including: 1) San Joaquin River Antioch Bridge, 2) Dumbarton Bridge, 3) Richmond - San Rafael Bridge, 4) West Crossing of the Bay Bridge, 5) San Mateo - Hayward Bridge, and 6) three Humboldt Bay Crossings. Woodward-Clyde of Santa Anna [4] was selected to perform seismic evaluations for Southern California bridge sites including: 1) San Diego Coronado Bridge, 2) Vincent Thomas Bridge, 3) Gerrald Desmond Bridge, and 4) Schulerheim Bridge. In addition to providing a characterization of local seismicity, these investigations are expected to provide both maximum credible rock spectra and representative rock acceleration histories for each of the sites.

The impact which incoherent seismic ground motions may have on the dynamic response of bridge structures is receiving serious attention by a number of investigators under Caltrans sponsorship. Eidinger and Abrahamson {10} identify the mechanisms of incoherence for long structures in terms of attenuation with distance from a fault, out-of-phase arrivals associated with non-horizontal wave fronts, scattering boundaries within a profile, and near-source effects associated with the passage of the fault rupture. These investigators are expected to begin a research project with Duggan of GENSYS/UENC [6] to evaluate the impact incoherence has on the dynamic response of the East Crossing of the Bay Bridge. This investigation will also focus on a state-of-the-practice assessment of the Bay Bridge to supplement the state-of-the-art investigation by UCB. As part of a separate UCB effort sponsored by Caltrans [7], Lysmer and Deng {11} have developed a new finite element method to perform 2-D analyses of ground response. This method utilizes "hyperelements" to reduce the requisite number of elements for large dynamic models, and therefore can be efficiently implemented on a microcomputer. This method is capable of modeling response to both inclined body waves and surface waves. Finally, Der Kiureghian [5] will utilize a newly developed response-spectrum method for multiple-support structures {12} for the seismic analysis of a viaduct in San Francisco. This new method recognizes the variability in ground motion associated with differing soil profiles over short distances as well as the incoherence effects previously discussed for longer structures.

4. Ground Motion Prediction

The significance of site amplification effects were fully recognized after the engineering community witnessed the concentration of destruction in localized regions underlain by soft soil deposits during both the 1985 Mexico City and the 1989 Loma Prieta earthquakes. The collapsed portions of the Cypress Freeway were founded almost exclusively within profiles containing soft clay soils. In response to these events, Caltrans began to re-examine its procedures for specification of ground motion, particularly for soft soil sites.

Caltrans utilizes a response spectrum approach for the seismic design of most bridge structures. Standard procedure since the 1970's involves specification of design spectral acceleration values from a family of "standard ARS" curves which appear in the Caltrans manual called Bridge Design Specifications {13}. The appropriate ARS curve is selected on the basis of both a seismicity map and the depth of alluvium at a site. Since the Loma Prieta event, site-specific ground response predictions are being developed for selected structures which are either founded on soft soil profiles or are identified as "important" (usually in terms of providing secondary life safety).

Caltrans is currently sponsoring several research projects related to geotechnical ground-motion prediction. This effort is a combination of both internal staff and contract projects directed toward improvements in site-specific material characterization capabilities, verification of analysis procedures, and development of improved standard ARS. Each of these topics will be discussed in this section after first providing some background on current site-specific procedures.

4.1 Current Caltrans Site-Specific Design Procedures

Site specific ground response predictions are performed within Caltrans by the Office of Geotechnical Engineering at DNTMR. Standard procedure {14} utilizes the program SHAKE {15, 16} along with site-specific characterization of both the input bedrock motions and the soil profile. The input bedrock motions are established using one of several alternative procedures, and typically involve formulation of a site-specific target spectrum based primarily on methodology originally proposed by Sadigh et al {17} and later updated by Geomatrix {18}. The target spectrum is scaled such that the spectral value at "zero" period matches the peak bedrock acceleration established on the basis of both seismic maps and various published attenuation relationships. Once the site-specific target spectrum is established, either a suite of at least three bedrock acceleration histories are established by modifying selected earthquake recordings to match the target spectrum, or a larger suite of recordings is selected and scaled to collectively "fill" various spectral regions of the target spectrum.

Soil profile characterization is accomplished through a combination of routine geotechnical investigation techniques and in situ seismic testing. Site stratigraphy is established using a combination of historical drilling logs, cone penetration data for softer near-surface layers, and conventional drilling and sampling techniques into bedrock. Low-strain modulus for the various stratigraphic units is established using one or more of a variety of in situ seismic techniques. High-strain normalized-modulus-degradation and hysteretic-damping properties of soils are established on the basis of published curves {19, 20}. Both sets of curves provide estimates of dynamic properties to approximately 1% shear strain, and must be extended to 10% shear strain in order to facilitate analysis of many sites of concern. This extension is made by assuming a stress-strain curve which accounts for either the measured or correlated strength of a soil under dynamic loading. (Please note that a previous reference {14} on this topic contains an error. If clarification is needed, feel free to contact DNTMR, Office of Geotechnical Engineering)

The soil-profile and bedrock-motion information established using the above procedures are input into the SHAKE program to determine free-field ground response. The sensitivity of the results to potential variations in material properties is typically considered. All analysis output is scrutinized for obvious errors as well as potentially excessive values of both shear stress and shear strain. A suite of output response spectra for the various input motions are then plotted, and engineering judgment is utilized to establish a design envelope which encompasses the majority of the spectral content exhibited by the record suite. Figure 1 presents example results from utilization of this methodology. The upper pair of spectral plots shows both individual response from a number of separate input motions along with a design envelope which is drawn to encompass the majority of spectral energy. The left-hand plot utilized acceleration histories which were modified to a target spectrum, while the right-hand figure utilized a larger suite of acceleration

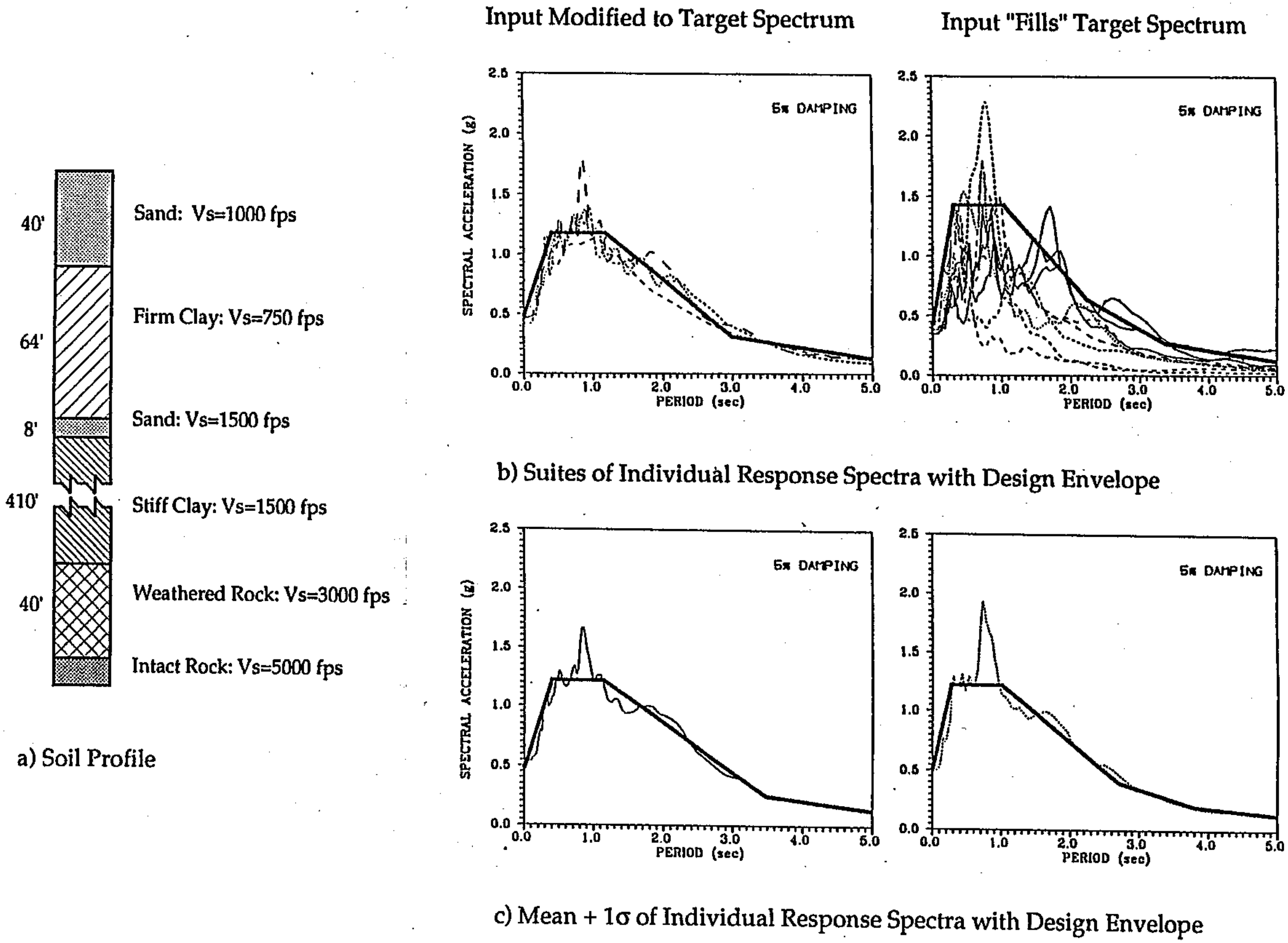


Figure 1. **Example Results for Site-Specific Ground Response Analysis Using Current Caltrans Methodologies (14).**

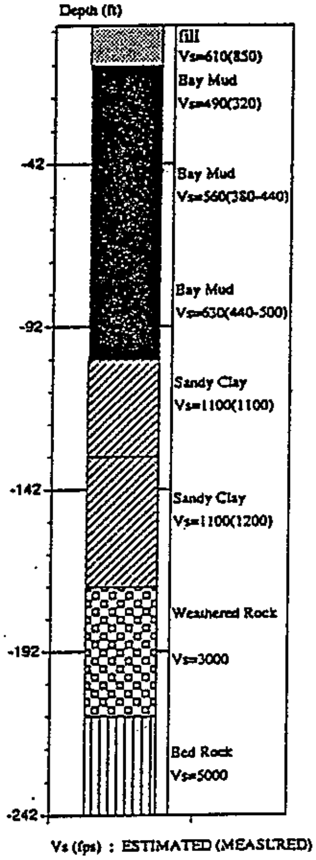
histories which collectively fill the target spectrum The lower pair of spectral plots show the mean plus one standard deviation of the individual response spectra from the upper figures along with an appropriate design envelope.

4.2 Site-Specific Material Characterization [8, 11]

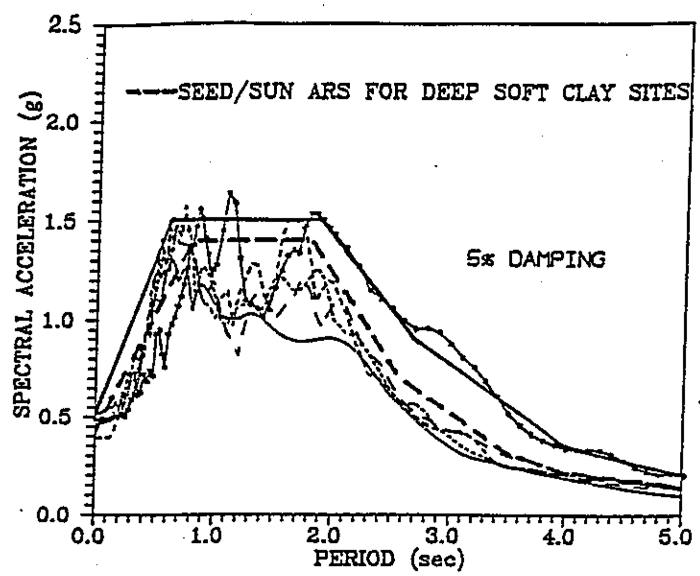
Three types of information are required by all ground response analyses: 1) input "bedrock" acceleration histories, 2) site stratigraphy, and 3) material properties for the various stratigraphic units. Issues related to appropriate characteristics of input motion are typically considered by seismologists, and uncertainties in specification are accommodated in design through modeling of several independent scenarios. Characterization of site stratigraphy is primarily constrained by the level of effort put into the geotechnical investigation rather than the current state of knowledge. Finally, the material properties of soils, typically expressed in terms of modulus and damping, have recently been recognized as having a profound impact on ground response predictions. Due to the highly non-linear behavior of soils with strain level, material properties are typically characterized separately for low-strain ($<10^{-3}$ %) and high-strain (10^{-3} % to ~10%) behavior. This subsection will briefly discuss two on-going research projects directed toward improvements in site-specific characterization of low- and high-strain material properties, particularly for soft soils.

Figure 2 presents results of an actual design case which illustrates the impact which modification of low-strain material properties can have on a site-specific response analysis. The analyses used to determine the spectral design envelopes shown in the upper and lower plots of Fig. 2 differ only in the values of low-strain modulus which were assigned to the upper strata of the profile. This level of analysis sensitivity prompted initiation of an internal minor research investigation [8] into the effectiveness of various seismic techniques used to establish in situ shear-wave velocity (which is directly related to low-strain modulus) of soil strata. This investigation focused on a side-by-side comparison of four methods for velocity determination including: 1) crosshole testing, 2) downhole testing with the seismic cone, 3) downhole testing using conventional borehole receivers, and 4) in-hole testing using the proprietary Oyo P-S Suspension Logger system. All data has been acquired, and results will be contrasted and compared with various established correlations. Additionally, the crosshole investigation at this site was performed along two mutually perpendicular orientations using a five-borehole array. These results will be examined for potential anisotropy in the horizontal plane. Pending results of this investigation, two additional sites are currently being considered for future side-by-side comparisons. Finally, it should be noted that low-strain damping values can also play a critical role in ground response, especially for deep alluvial profiles. At this time, no work is being sponsored by Caltrans on this topic, however, an investigation by EPRI is underway.

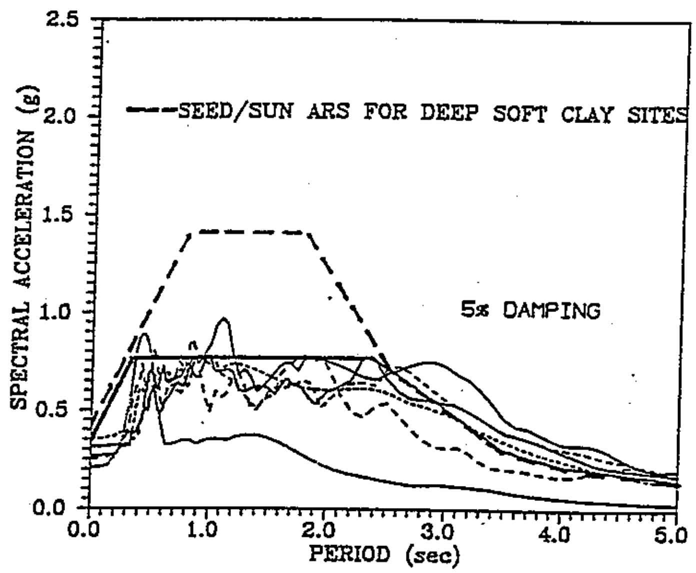
The impact which high-strain properties can have on ground response predictions is illustrated in Figure 3. Each of the three plots along the upper row of



a) Soil Profile

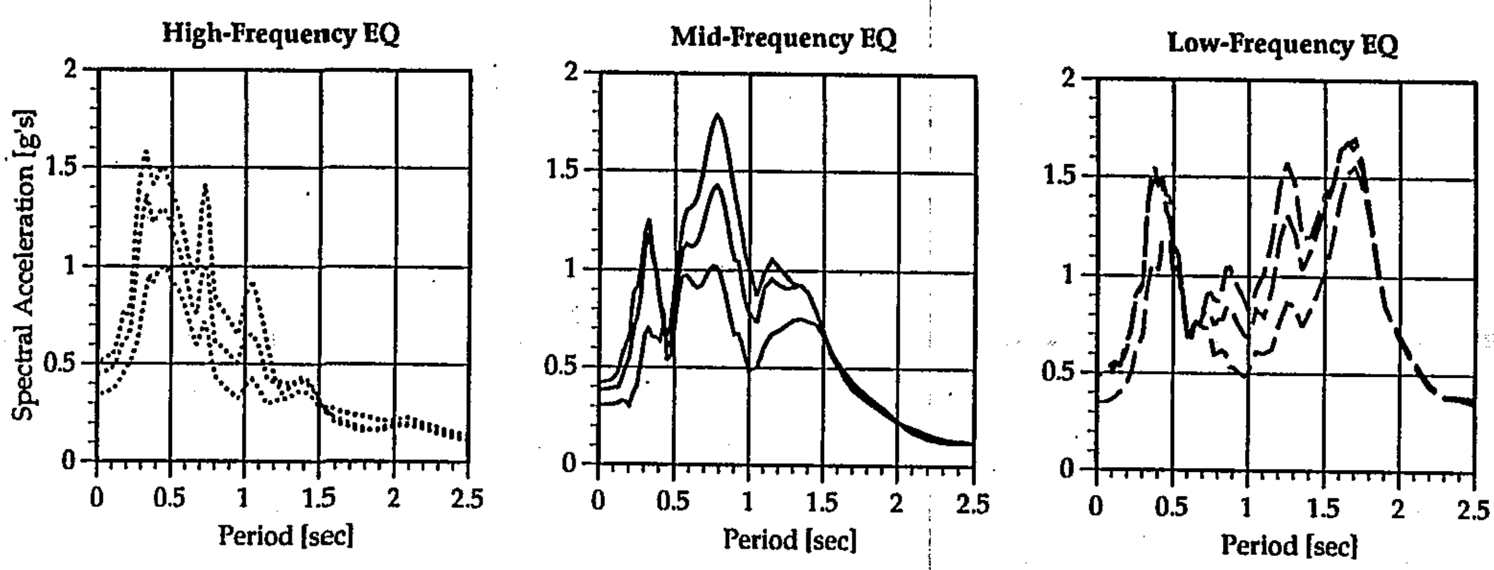


b) ARS Based on Estimates of Shear Wave Velocity

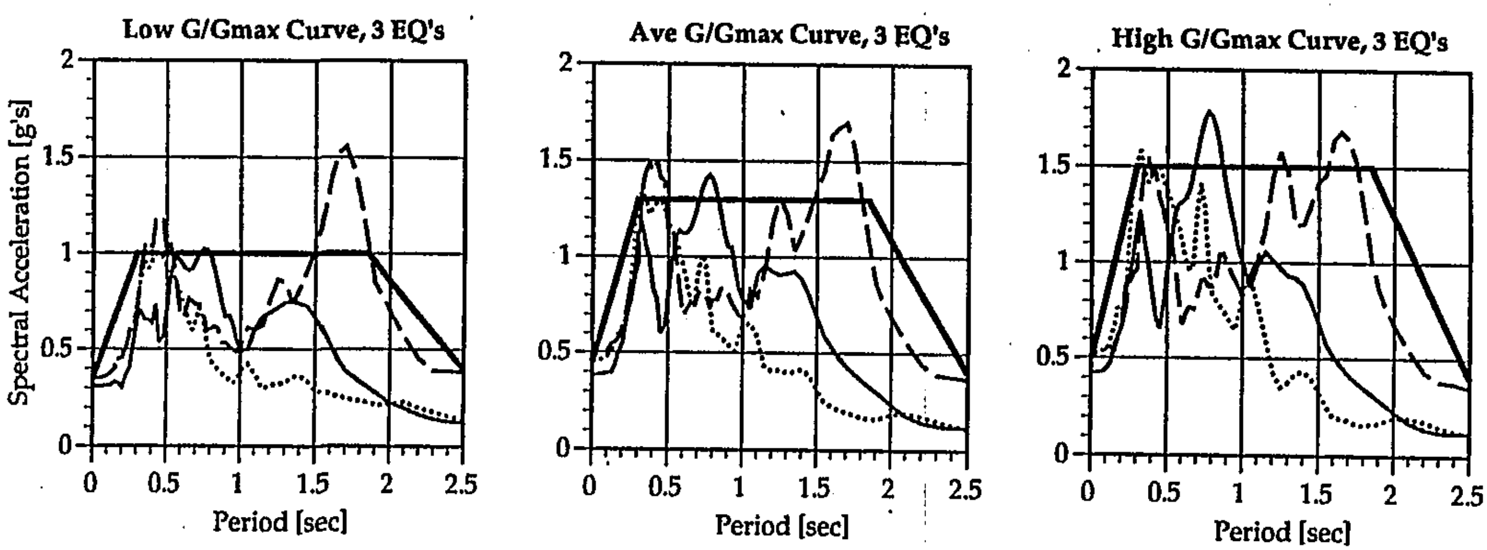


c) ARS Based on Measured Shear Wave Velocity

Figure 2. Design Example Illustrating the Impact of Low-Strain Modulus on Response.



a) Effect of Varying Modulus Reduction Curve for Each of 3 Earthquakes (PBA=0.4g).



b) Impact of Varying Modulus Reduction Curve on Design Envelope.

Figure 3. Synthetic Example Illustrating the Impact of Typical Range in Modulus Reduction Curves on Response.

the figure present results of three separate ground response analyses for a single idealized Bay Area site. Within each plot, high-strain properties were varied according to published ranges {19, 20} of material properties for a moderately-plastic marine clay. Note that the same low-strain modulus and implied strength (at 10% strain) are used for all analyses. Between plots in the upper row, the specified input motion is varied from left to right to include earthquakes rich in a short, medium, and long period energy, respectively. Note that all input motions were scaled to a moderate value (0.4g) of peak bedrock acceleration. The same spectra shown in the upper row of plots are reorganized into the lower row such that a single plot shows spectra for each of the three input motions using a common set of high-strain material properties. These results clearly indicate a significant level of sensitivity of ground response calculations to high-strain properties. Note that while the results presented here were determined using SHAKE, very similar results were determined using a fully non-linear analysis.

Recognition of the impact which high-strain properties have on ground response predictions led to the recent initiation of a major research contract with the University of California at Davis [11]. This project will work toward development of a prototype tool for direct in situ measurement of shear-modulus degradation and damping curves for soft to medium-stiff clays over a wide strain range. The focus of the project on in situ rather than laboratory measurements is intended to both overcome many potentially degrading effects of sample disturbance on material properties, and to provide a tool which could be utilized for site-specific investigations in a timely manner. Currently, the project staff is examining the feasibility of various alternative tool configurations.

4.3 Analysis Verification [10, 13, 14]

Caltrans currently makes extensive use of the program SHAKE for design-level site-specific ground response prediction. This program uses an equivalent linear approximation for the stress-strain behavior of soil. Although recent publications {21, 22, 23} support the adequacy of this procedure for analysis of moderate-level earthquakes such as the Loma Prieta event, questions have been raised about its appropriateness for higher levels of acceleration. This is particularly true for profiles containing materials such as soft clays and loose sands which may undergo large strains during excitation. Alternatively, a number of "fully non-linear" procedures exist which include more realistic models of soil behavior under high strain. These models should be capable of better estimates of spectral response as well as provide reasonable estimates of residual displacements caused by plastic strains. However, these analyses have been notoriously difficult to implement on a design level due to both the large number of parameters required to characterize soil behavior (typically 10 to 20), and the numerical subtleties of running the code. Furthermore, there is a complete lack of supporting high-strain field data for verification of these analyses under relevant conditions. Since the potential benefits of adopting fully non-linear analyses are great, Caltrans has shown interest in sponsoring verification studies which might lead to more confidence with these procedures.

Three research projects are either currently underway or being considered by Caltrans which will attempt to provide verification of ground response procedures. The first is a contract research program [10] with UCD to perform a series of centrifuge experiments which will record the behavior of six separate soil profiles at several depth intervals for each of four levels of shaking ranging from 0.1g to 0.6g. Results from these experiments can be utilized immediately for calibration of existing models. The remaining two research projects under this category are in the proposal stage, and are closely related. The first project [13] proposes a side-by-side comparison of forward response predictions for a single field site using a number of alternative programs. The site under consideration is the "Islais Site" which has been well characterized as a result of the seismic testing program [8]. The second project [14] proposes to install an array of strong motion sensors at this same site for purposes of verifying analysis predictions. Although the benefits of this type of study are subject to the occurrence of a large magnitude event (estimated to be ~60% probability within the next 30 years {24}), the unique profile at this site provides an excellent long-term verification opportunity which will incorporate macroscopic effects not well modeled in laboratory settings.

4.4 Improvements in Standard ARS [7, 9, 12]

Considering the thousands of Caltrans structures of various sizes throughout the State, comprehensive site-specific evaluations of ground motion for all bridge sites must be considered as infeasible, and use of some form of standardized response spectrum approach must be adopted for routine bridge design. Three research investigations are currently underway to examine potential improvements in Caltrans standard ARS.

The most comprehensive of the investigations has been performed by Seed et al. of UCB as part of the research project focused on the behavior of deep soil sites in San Francisco [7]. This project, which is nearing completion, initially concentrated on the response of soft soil profiles, but has since been expanded to consider stiff soil profiles as well. Early work {21, 25, 26} concentrated on both establishment of a set of typical properties for Bay Mud, and verification of modeling procedures through comparison with Loma Prieta case histories. Subsequent work has focused on a comprehensive series of ground response analyses for a number of different combinations of idealized soil profiles and earthquake magnitude. Analyses were performed using SHAKE for low to medium level inputs, and with a modified version of DESRA-2 {27} for medium to high levels of acceleration. Input motions for each level of acceleration were selected from a database of recorded and synthetic records so that the need for amplitude-scaling was minimized. Soil properties were assigned on the basis of correlations established during the first phase. Results were grouped according to stratigraphic criteria and viewed in terms of normalized spectra combined with a peak-acceleration site-amplification factor similar to ones previously published {22, 28, 29}. Based on this work, a new set of generic seismic design guidelines are being proposed by Seed and his co-investigators. A preliminary draft of this proposal appears in Table 2 and Fig. 4, and currently proposes use of six separate site classes having ten identifiable site profile combinations. Each site class is associated with both a normalized spectral envelope and a magnitude-dependent amplification factor. Seed {30} indicates that modifications to these guidelines are forthcoming, so the information presented herein should be viewed as tentative. These recommendations (and any future revisions) will be independently reviewed within Caltrans through examination of a database of recent case histories for which site-specific analyses are available.

Two minor research projects regarding standard ARS have recently been initiated by staff at DNTMR. The first project [9] examines the impact which updated material properties for plastic soils have on Caltrans standard ARS. The existing standard ARS curves were developed {31} under the assumption that all alluvium could be conservatively characterized using the high-strain material properties of sands which, at the time, were thought to behave more elastically than clays. Since soft-soil sites are now routinely characterized using a site-specific analysis, the primary focus of this investigation will be on the response of stiff soil profiles for which standard ARS curves are still commonly employed. In particular, the adequacy of the existing curves will be assessed both relative to results of selected site-specific analyses, and with results from a series of analyses using synthetic profiles containing plastic strata of varying thickness. The second minor project [12] will focus on a current review of seismic design provisions which appear in various world-wide building codes. The objective of this project is to assimilate a variety of perspectives regarding design specification of ground motion.

5. Soil-Structure Interaction

The phrase "soil-structure interaction (SSI)" is arguably one of the most vague terms used by the Civil Engineering profession. It encompasses many different categories of both soil and structural problems and solution approaches which are grouped under one label. For purposes of this paper, three SSI problems of interest to Caltrans will be discussed: 1) foundation flexibility, 2) pile survivability, and 3) substructure effects on ARS.

5.1 Foundation Flexibility [15, 16, 17, 19]

In recent years, there has been increasing recognition of the impact which the flexibility of foundation elements such as pile groups and abutments have on the seismic performance of bridges. In the past, Caltrans had assumed that foundation systems provide a "fixed" boundary for purposes of dynamic analyses. Current Caltrans procedures require consideration of foundation-flexibility effects in design. These effects can significantly increase both the structural period and deck displacements, as well as cause a redistribution of load within the structure relative to the fixed-boundary case. Numerical parametric studies completed by the Cygna Group [16]{32} using the general-purpose linear structural analysis program SAP {33}

Site Class	Site Condition	General Description	Site Characteristics[1,2]
(A_0)	A_0	Very Hard Rock	$V_s > 5{,}000$ ft/sec
	A_1	Rock and/or Weathered Rock.	2,500 ft/ sec $\leq V_s \leq 5{,}000$ ft/sec
A	A_2	Stiff, Shallow Soil.	$H_{soil} \leq 50$ ft, and $V_s \geq 800$ ft/sec (in all but top few feet.[3])
	B_1	Deep, Primarily Cohesionless[4] Soils. ($H_{soil} \leq 250$ ft.)	No "Soft Clay" (see Note 5), $H_{cohesive\ soil} < 0.2\ H_{cohesive\ soil}$, and $H_{cohesive\ soil} < 50$ ft
B	B_2	Medium Depth, Stiff Cohesive Soils and/or Mix of Cohesionless with Stiff Cohesive Soils; No "Soft Clay".	$H_{all\ soil} \leq 150$ ft, and V_s (cohesive soils) > 500 ft/sec. (see Note 5.)
C	C_1	Medium Depth, Stiff Cohesive Soils and/or Mix of Cohesionless with Stiff Cohesive Soils; Thin Layer(s) of Soft Clay	Same as B_2 above except 0 ft $< H_{soft\ clay} \leq 10$ ft (see Note 5.)
	C_2	Deep, Stiff Cohesive Soils and/or Mix of Cohesionless with Stiff Cohesive Soils; No "Soft Clay".	$H_{soil} > 150$ ft, and V_s (cohesive soils) > 500 ft/sec.
D	D_1	Soft, Cohesive Soil.	10 ft $\leq H_{soft\ clay} \leq 90$ ft, and $A_{max,\ rock} \leq 0.3$ g, or [$A_{max,\ rock} \leq 0.45$ g and $M \leq 7.5$]
	E_1	Very Deep, Soft Cohesive Soil.	$H_{soft\ clay} > 90$ ft (see Note 5.)
(E)[6]	E_2	Soft, Cohesive Soil and Very Strong Shaking	$H_{soft\ clay} > 40$ and either: $A_{max,\ rock} > 0.45$ g, or $A_{max,\ rock} > 0.3$ g and $M > 7.5$

1 H = total (vertical) depth of soils of the type or types referred to.

2 V_s = seismic shear wave velocity (ft/sec) at small shear strains (shear strain ~10^{-4}%).

3 If surface soils are cohesionless, V_s may be less than 800 ft/sec in top 10 feet.

4 "Cohesionless soils" = soils with less than 30% "fines" by dry weight;
"Cohesive soils" = soils with more than 30% "fines" by dry weight, and PI (fines) ≥ 15%.

5 "Soft Clay" is defined herein as cohesive soil with: a) Fines content ≥ 30%
b) PI (fines) ≥ 20%, and
c) $V_s \leq 500$ ft/sec.

6 Site-specific geotechnical investigations and dynamic site response analysis are strongly recommended.

Table 2. Proposed Simplified Site Classification System (from Seed {30})

Effective Peak Ground Acceleration

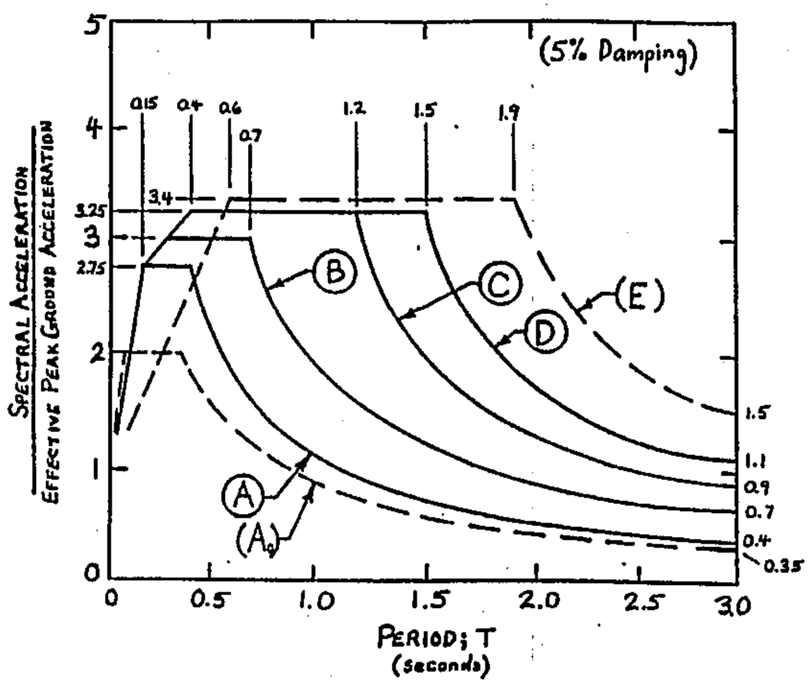
$$PGA_{eff.} = [(A_{max,\ rock})(F_A) + 0.04g$$

$$\text{where } F_A = \frac{A_{max}}{A_{max\ rock}}$$

A_{max} Amplification Factors (F_A)

Site Conditions \ $A_{max,rock}$	0.05 g	0.1 g	0.2 g	0.3 g	0.4 g	0.5 g	0.6 g	0.7 g
A	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
B, C_1	1.5	1.5	1.25	1.13	1.04	0.94	0.90	0.86
C_2, D, E	3.0	2.3	1.5	1.2	1.0	0.86	0.76	0.71

Site-Dependent Design Elastic Response Spectra



PGA vs. $A_{max,\ rock}$ for Defined Site Classes

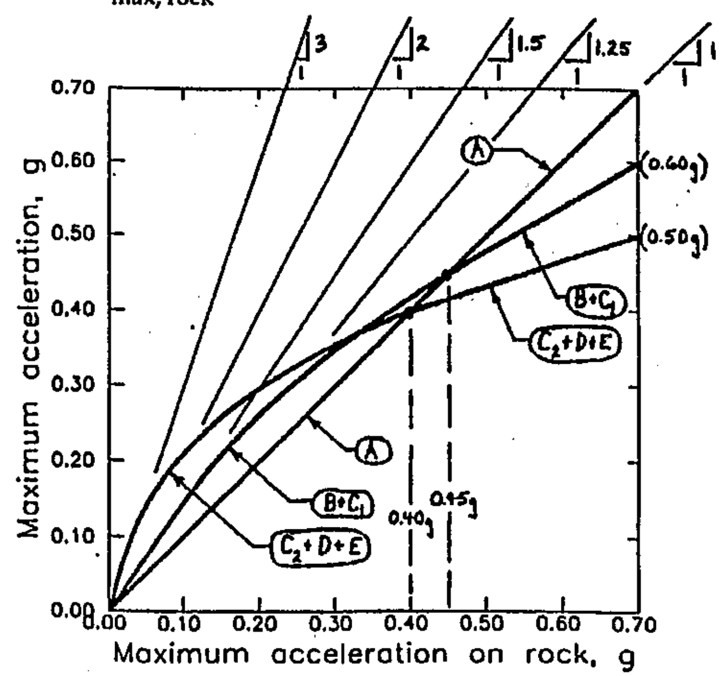


Figure 4. Proposed Method for Standard Specification of Site Response. (from Seed [30])

illustrate the impact which foundation-flexibility effects can have on selected dual-level bridge designs. This and other work indicates that fundamental mode periods of particular bridge designs shift between 40% and 300% relative to the fixed case. This period shift can profoundly affect the value of column base shear determined from a response spectrum.

Incorporation of foundation flexibility effects into structural design can be implemented using solutions exhibiting a wide range of sophistication. Ideally, a structural analysis should consider both the highly non-linear stress-strain behavior of soil as well as the pile-soil-pile interaction ("group effects") problem. Comprehensive consideration of this problem is generally impractical for design-level calculations, therefore, considerable effort is expended in identifying an appropriate level of analysis which adequately predicts response behavior without incurring excessive computational sophistication.

Current Caltrans design methodologies for column footings {34} utilizes perhaps the simplest approach to foundation flexibility where axial, lateral and rotational elastic "soil springs" are specified at each foundation boundary. Spring stiffness values are estimated using either the computer program GROUP1 {35} which utilizes P-Y and T-Z curves for soil-pile interaction, or a combination of methods which estimate foundation performance on the basis of Caltrans minimum axial performance criteria for piles and translational stiffness using modifications to methods presented by Lam et. al. {36} and Broms {37, 38}. Current Caltrans design guidelines for abutments utilize a similar soil-spring concept with empirically-derived values for horizontal stiffness (200 kips/in per lineal foot of wall width) and ultimate dynamic capacity (7.7 ksf).

Caltrans-sponsored research on the topic of foundation flexibility primarily examines either the applicability of current design procedures or assesses alternative design methodologies. Penzien [15] had investigated both the linear substructure method and the non-linear "hybrid model" for developing frequency-independent impedance matrices for substructure components to be used in the non-linear bridge analysis program NEABS {39}. Coast Analytics [17] is developing procedures to examine the SSI effects of a particular bridge structure (to be determined) using the finite element program SATURN {40}. This program can accommodate the fully non-linear behavior of soil including pore-pressure build-up and liquefaction. Martin et al. [19] propose to utilize the finite element program LINOS {41} to examine the soil-structure interaction behavior of various abutment configurations. After performing sensitivity studies pertinent to retrofit evaluations and new design criteria, simplified abutment modeling procedures are to be developed and checked using the program SEISAB {42}.

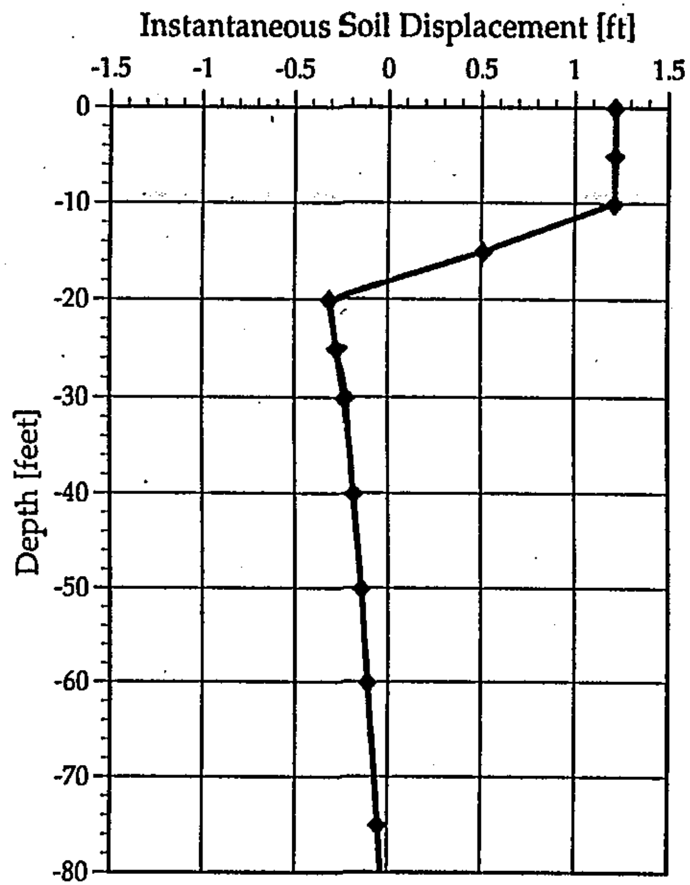
5.2 Pile Survivability Under Seismic Load [2, 20]

Pile survivability under seismic load is a soil-structure interaction issue which is separate from the effects which foundation flexibility have on structural response. The objective of a seismic pile-survivability study is to determine transient profiles of shaft deformation, shear, and bending moment for the foundation which are caused by the relative lateral movement between the free-field soil and the pile system during seismic events. This general analysis is also applicable to the problem of displacements caused by liquefaction and lateral spreading. It is important to note that this problem is different from conventional lateral response analyses which account for the superstructure load only.

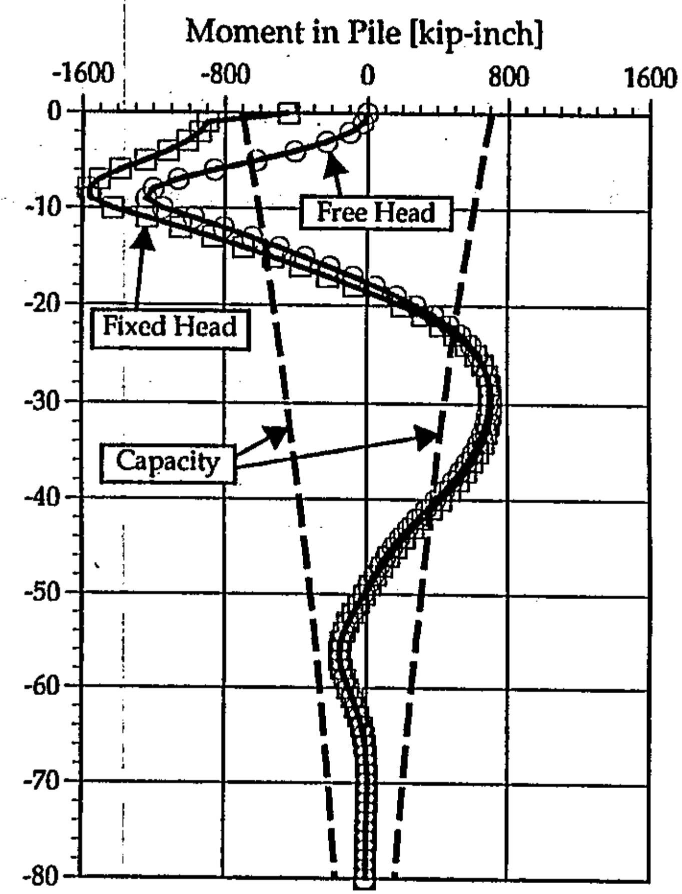
Recent analyses of several Caltrans bridge foundations performed by Slyh and Jackura of DNTMR indicate that certain pile types (typically timber and under-reinforced concrete of various configurations) are susceptible to unacceptable damage during design seismic events, and therefore require retrofit. Figure 5 presents example results of this type of analysis for a timber pile. These results are based on a P-Y analyses using the computer program BMCOL76 {43} where the profile of "soil spring" supports is deflected according to a specified displacement field indicative of worst-case free-field soil motions. At this time, the critical displacement profiles are estimated using two alternative methods which utilize response calculations estimated with SHAKE. The first alternative specifies a displacement profile by integrating peak free-field strain values over depth. The second method considers differential displacement profiles determined at various times from double-integrated acceleration histories. Pile group effects are estimated on the basis of static interaction factors.

An internal minor research project [20] recently proposed by Slyh of DNTMR will document the aforementioned methodology as well as assess alternative approaches. In particular, this project will focus on: 1) alternative procedures for estimating the critical displacement profile, 2) alternative assumptions regarding group effects, and 3) a comparison of both results and useability with existing comprehensive dynamic-analysis programs such as SPASM {44} and FLUSH {45}. Additionally, future investigations will attempt to examine the problem of progressive failure of brittle pile groups where loads are redistributed to inner piles as outer piles within the group are failed.

The pile-survivability of the very large pile groups of the East Crossing of the Bay Bridge is being investigated by Lysmer and Chin {46} as part of the overall seismic assessment [2, Ph2]. Due to the exceptionally large numbers of piles in each group (between 297 and 625), careful consideration of group-effects is critical to overall response and survivability. These investigators are developing a numerical model which will examine the response of a single pile in an infinite field of piles. This model will be capable of handling the redistribution of stress within the pile group caused by non-linearities and plastic flow of the soil as well as slip at the pile/soil interface.



a) Critical Transient Free-Field Displacement Profile.



b) Instantaneous Moment in Pile vs Pile Capacity.

Figure 5. Example of a Pile Survivability Analysis for a Timber Pile Subjected to Large Localized Displacement.

5.3 Substructure Effects on ARS [18]

Caltrans routinely employs the response spectrum approach to the seismic design of bridge structures in the form of either standard or site-specific ARS. Since these response spectra are representative of free-field motion, there is an implicit assumption that the foundation "tracks" free-field motion and that no soil-pile interaction effects occur. This assumption is reasonable for firm soil profiles in which pile systems are likely to comply with dynamic soil strains. However, this is not necessarily the case for sites underlain by soft-soil profiles where substructure stiffness may significantly affect foundation response at ground level.

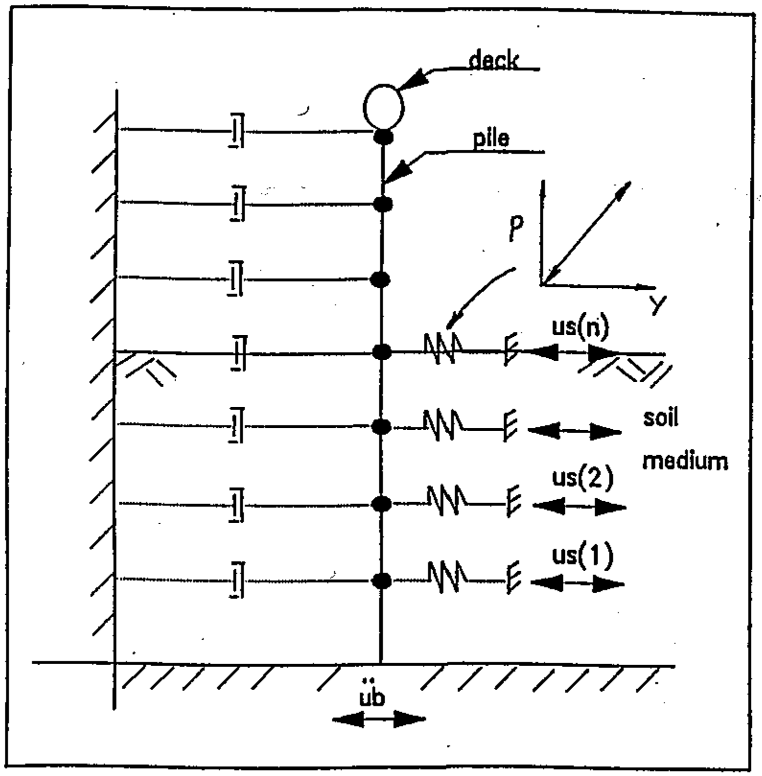
Slyh and Jackura at DNTMR [18] have begun evaluation and modification of numerical procedures to include soil-structure-interaction effects in the determination of site-specific foundation response and ARS. This investigation is an extension of the work initiated by Cafe {47} and utilizes modified versions of the BEAM1DYN program. Refinements to the program include changing the soil elements to accommodate non-linear hysteretic behavior. Preliminary parametric studies indicate that stiff foundation systems within soft-soil profiles experience significantly different acceleration and displacement behavior than that of the surrounding soil in the free field. Fig. 6 presents example results of this behavior for one particular foundation-design/soil-profile combination. Results for this case show significant amplification over free-field motion at periods of less than 1 second, and attenuation of motion for longer periods.

The impact of superstructure inertial "feedback" to the foundation system is also being investigated as part of this project. Preliminary parametric studies which include representative mass and stiffness elements to model the superstructure have shown further significant changes in pile-cap response. These effects appear to be a function of both the added mass and stiffness independently rather than to the stiffness/mass ratio commonly utilized in the single-degree-of-freedom model. To accommodate this behavior, the use of a 3-D surface of peak elastic structural response versus both representative mass and stiffness is under consideration.

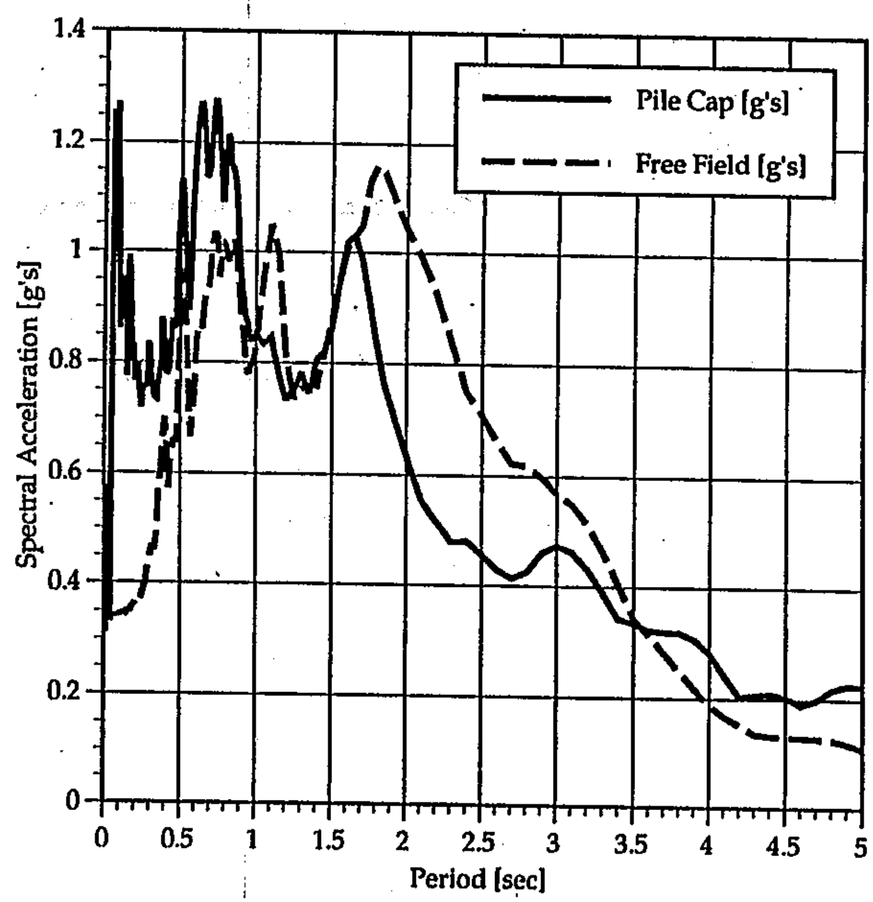
6. Review of Design Procedures [21, 22]

Two separate contract research projects have been initiated by DOS to review various aspects of Caltrans bridge design procedures. The first study by the Applied Technology Council (ATC) [21] is broad based and provides a complete review of the entire bridge design process ranging from rehabilitation prioritization to requirements for design checks. The second study by Dames and Moore (D&M) [22] is more narrowly focused on the behavior of short bridge overcrossings. Portions of both of these studies are relevant to seismic foundation design.

The ATC study involves seven separate subcontractors, one for each of seven areas identified for assessment. Geospectra, Inc. was chosen to review Caltrans seismic loading guidelines. Preliminary findings by Singh {48} indicate concerns



a) Linear P-Y Model Used for Analysis of SSI Effect on ARS. (After Cafe (47))



b) Spectral Response at Ground Level for Free-Field and Cap Motion

Figure 6. Example of the Effect of Pile Stiffness on Response Using a Linear P-Y Approximation.

regarding: 1) the representativeness of Caltrans standard ARS, 2) the use of a "maximum credible" design earthquake, and 3) the use of both target spectra and SHAKE analysis for estimation of site-specific response spectra. This report also discusses the applicability of probabilistic approaches for specification of design earthquakes, key issues related to site effects, and appropriate development of strong-motion records for site-specific response analyses.

Earth Mechanics, Inc. was selected as the ATC consultant for foundation design and rehabilitation. Lam and Martin {49} have reviewed all Caltrans documents pertaining to the standard design practice for substructure elements. Relevant Caltrans guidelines and procedures related to abutments, pile footings, drilled shafts, spread footings, retaining structures, and ground failure hazards are summarized and discussed individually. Key recommendations include the need within Caltrans: 1) for both expansion and improved synthesis of information related to foundations which currently appears in a number of separate documents, 2) to verify abutment stiffness and damping parameters, 3) to examine both the lateral stiffness and lateral capacity of pile groups through a destructive testing program so as to identify the separate contributions provided by the individual piles and the pile cap, 4) for routine determination of site-specific ultimate capacity estimates for piles, especially for uplift loading, and 5) for improved design guidelines for footing-connection details to provide the requisite uplift capacity to resist overturning moment.

The D&M study is focusing on evaluation procedures used by Caltrans to identify retrofit needs for two-span short bridge overcrossing (SBO) structures. Current evaluation results for selected structures have implied a need for retrofit of thousands of older SBO's constructed throughout California. D&M plans to assess the current seismic evaluation procedure for SBO structures, and to develop a new procedure which may lead to a more "realistic basis" for assessing retrofit needs. In addition to purely structural considerations, this study will focus on improvements in the modeling of foundation flexibility at both the abutments and central column, as well as the appropriateness of using 5% modal damping in the specification of ARS design spectra.

7. Structural Aspects of Substructures [23, 24]

Two contract research projects sponsored by DOS are currently underway which focus on structural aspects of two different substructure systems. The first is a project through UCD [23] which is examining the behavior of pile-extension substructures, and the second is a project through UCSD [24] which is examining the structural performance of bridge column footings.

The failure of the Struve Slough Bridge during the Loma Prieta event focused attention on the performance of "pile cap extension" substructures. These substructure elements are simply columns which extend from individual piles at ground line to a bent cap located directly beneath the deck beams. Ramey et al {50} at

UCD are performing experimental investigations to determine the actual bending/shear strength behavior of pile extensions which were "harvested" from the Struve Slough Bridge. Additional experiments on newly-constructed members will be performed to assess both a scheme to rehabilitate cracked column sections using epoxy pressure injection methods, as well as various retrofit schemes involving confinement strategies for increased strength and ductility.

The seismic performance of conventional footing designs is the focus of a combined analytical and experimental research program underway at UCSD. Priestley et al {51} are investigating potential design problems and alternative retrofit strategies for various footing configurations. The potential design problems under investigation include: 1) inadequate anchorage of longitudinal column rebar in the footing, 2) inadequate shear strength of the joint region under the column, 3) inadequate footing flexure and shear strength, and 4) inadequate restraint against overturning. Experimental work will utilize large-scale laboratory models including tests on a rubber substrate to investigate footing performance under rocking motion.

8. Field Load Tests

A key component in Caltrans' seismic research program has been the use of field load tests as a means to verify modeling and design assumptions. The following subsections will briefly discuss five projects related to substructure performance.

8.1 Cypress Footings Lateral Load Tests [25]

The demolition of the Cypress Street Viaduct after the Loma Prieta event provided a unique opportunity to perform full-scale load tests on typical pile-group foundations used for bridge structures. Under tight time constraints, Abcarius {52} supervised lateral load testing of foundation groups at two separate bent locations. Testing at one location involved three pile caps with ~60-ft long piles penetrating into clayey material, while the second location involved two pile caps with ~15-ft long piles set into sandy silt. All piles were 12-inch-diameter closed-ended concrete-filled standard steel pipes, and the individual pile groups consisted of between 10 and 17 piles.

Testing was performed by laterally jacking between pile caps at each bent location with a pair of hydraulic rams while measurements of cap displacement and ram pressure were recorded for one load cycle. The primary objective was to verify the design assumption of 5 kips/pile at 1/4-inch cap deflection. The load tests indicated that average measured lateral pile capacity was between 17 and 26 kips per pile at 1/4-inch cap deflection, while average ultimate lateral capacities exceeded 35 kips per pile. Subsequent axial tension testing of single piles at each of three separate bent locations was performed by staff of DNTMR. Although the implemented lateral-load-test program precluded determination of individual pile capacity, group effects, soil P-Y behavior, or the behavior of the pile group under repeated load cycles, results from these tests clearly demonstrated that Caltrans' design criteria of 5 kips/pile was conservative.

8.2 Meloland River Overcrossing Dynamic Testing [26]

The Mololand River Overcrossing (MRO) is a monolithic, two-span, reinforced concrete box girder bridge which is located along Interstate Highway 8 adjacent to the Imperial Fault. This bridge became the focus of research interest after strong-motion accelerometers located at this site successfully recorded both free-field and bridge-deck motions during the 1979 Imperial Valley earthquake (M=6.8). Since that time, Caltrans has sponsored research which has investigated the response of this bridge under both low-amplitude ambient vibrations {53} and under medium-level forced vibration tests {54}. This research has led to general recognition within Caltrans of the effects which soil-structure interaction of bridge abutments have on the overall seismic response of bridges.

The primary focus of research on the MRO has been the determination of global response characteristics such as structural mode shapes, natural frequencies, and modal participation factors. However, back-analysis of the performance of this structure at the various levels of excitation has been used to estimate foundation flexibility values (translational and rotational stiffness) for both the central pier and bridge abutments {55, 56, 57, 58}. This and other case histories have provided a baseline for comparison of alternative design methodologies for estimation of foundation flexibility values {59}. Key findings from this work include the documentation of a significant reduction in the fundamental transverse frequency of the bridge (from ~3.4 Hz to between 1.3 and 2.6 Hz) as vibration amplitude increases. This reduction is primarily attributed to large decreases in foundation stiffness values at high strain.

8.3 Terminal Separation Lateral Load Test [27]

The Terminal Separation is a series of interwoven ramps connecting I-80 with downtown San Francisco at the western terminus of the Bay Bridge. This structure was closed after the Loma Prieta event due to concern over design details which were similar to the collapsed Cypress Freeway. Cooper {60} provides an excellent discussion of both the decision to replace the existing structure, as well as the unique features of the replacement design. The new design utilizes a dual-independent framing concept with increased span lengths relative to the existing structure. The alignment crosses several stratigraphic profiles, and requires use of six different site-specific ARS over its 0.7-mile length. The combination of longer spans, tight alignment tolerances, and high seismic design loads necessitated careful analysis of the lateral capacity of both drilled shaft foundations for rock sites and pile-group foundations for soil sites. Preliminary analyses for the drilled shafts (based on limited P-Y behavior data for fractured rock) indicated the need for an embedment length into the Franciscan rock of six diameters or approximately 45 feet. Estimated costs for drilled shaft construction exceeded $3.5 million.

To verify modeling assumptions regarding the behavior of the fractured rock at the Terminal Separation, a full-scale lateral load test of drilled shafts was implemented by Speer of DNTMR at the Rincon Hill site. The test utilized a pair of highly-instrumented 7-ft-diameter drilled shafts embedded directly into fractured bedrock (surface alluvium removed) to a depth of approximately 45 feet. Instrumentation internal to each of the shafts included strain gages fixed to the reinforcing cage at each of six radial positions around the shaft at either 9-inch or 18-inch depth intervals, Carlson gauges located at each of four radial positions around the shaft at 36-inch intervals, and a slope inclinometer casing down the center of each shaft. Figure 7 illustrates the loading scheme where the shafts were pulled together using a pair of hydraulic rams which stressed a pair of multi-strand cables which passed through and were locked-off to each of the shafts. A pair of load cells measured tensile load on each of the two cables, and displacements of each of the two shafts were measured at three locations above ground line on each of two sides of the shafts.

Figure 8 presents preliminary load-displacement results for one shaft during the load sequence which consisted of a series of four load-unload loops of increasing magnitude to a maximum value of approximately 2000 kips. The final load cycle caused a lateral ground-level displacement of approximately 2 inches, and produced a plastic hinge in one shaft at a depth of approximately 5 feet below the top of rock. Figure 9 presents preliminary results of both strain and displacement profiles for one shaft for each of the four peak loads. These data indicate that the peak moment occurred at a depth of approximately five feet, and the entire load was shed at a depth of approximately 20 feet below top of rock. Additionally, forward predictions of shaft load-deformation behavior using pressuremeter-derived P-Y curves and COM624 analysis appear to correlate well with the measured data for all load ranges. A final report incorporating more refined analysis of the over 100,000 data points acquired at this site is being prepared by Speer, and will be published in 1993. Presuming the shaft tip elevations can be raised between 10 and 15 feet, the direct cost savings resulting from this investigation are estimated to be in the range of $1 million.

8.4 Large-Scale Modeling of Bridge Abutment Behavior [28]

The sensitivity of bridge-response calculations to assumed boundary conditions at abutments has highlighted the need for direct physical measurements of abutment behavior under cyclic loading. In response to this need, a joint research effort involving Caltrans and the University of California at Davis (UCD) was initiated to systematically examine the response characteristics of a "near full-scale" model of a typical California-type bridge abutment system {61}. In particular, this experimental program will focus on both the evaluation of longitudinal, transverse, and rotational stiffness, as well as ultimate load capacity provided by the abutment. These measured values will be used to assess existing analytical or empirical models including current Caltrans bridge modeling guidelines (stiffness of 200 kips/in/ft of width, and dynamic capacity of 7.7 ksf). These results, in particular the ultimate

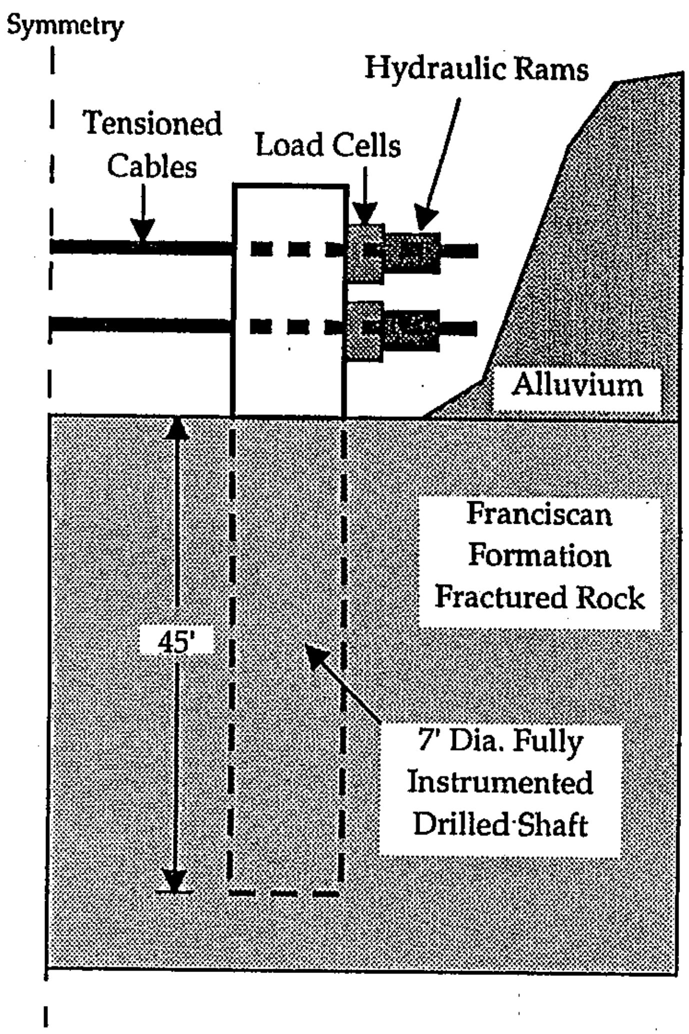


Figure 7. Conceptual Configuration of Terminal Separation Lateral Shaft Load Test

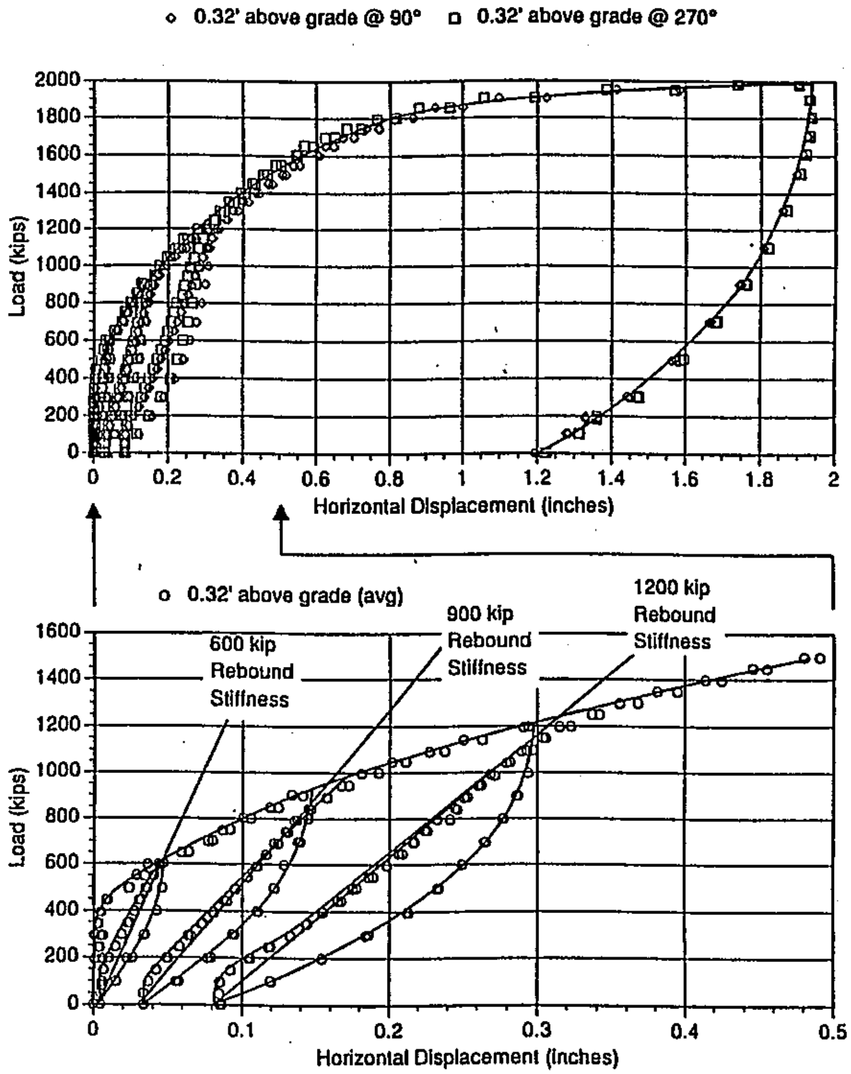


Figure 8. Shaft Head Load vs Horizontal Deflection Near Ground Line for Shaft B

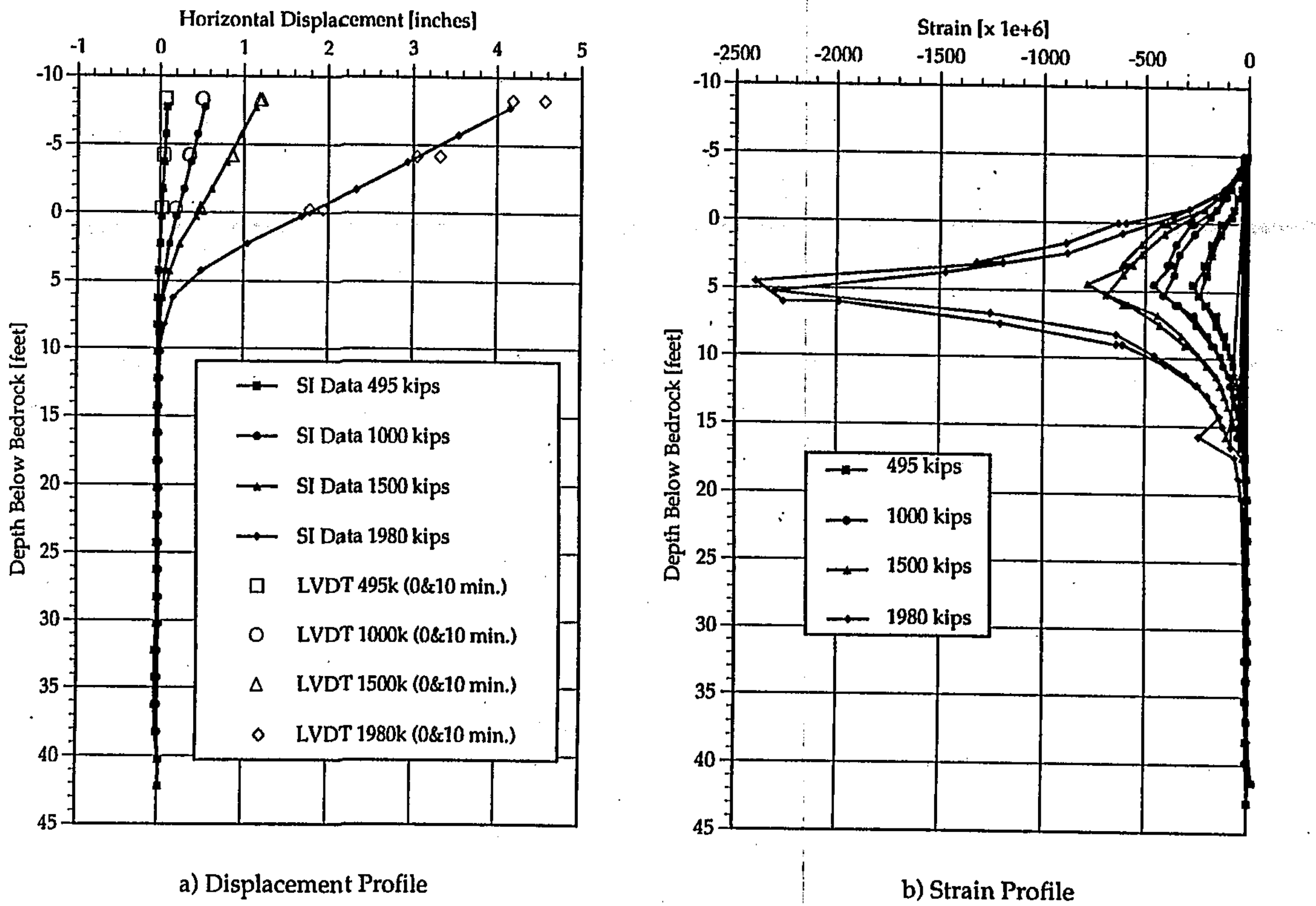


Figure 9. Terminal Separation Lateral Load Test Results. Displacement and Strain Profiles for 4 Peak Load Levels.

capacity, could have significant impact on the number of California bridges which will require retrofit.

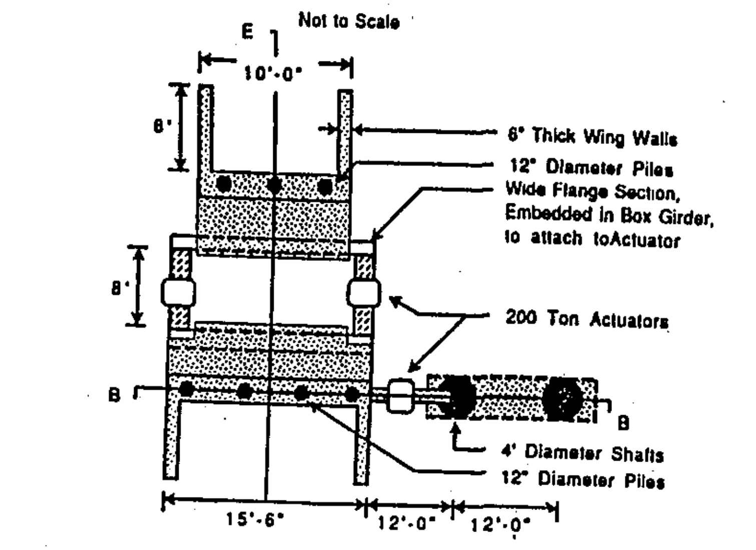
The test facility which is located at UCD has been carefully planned to enable independent examination of several critical factors affecting abutment performance. Figure 10 illustrates the general layout of both the primary abutment facility and the supplemental pile facility. The primary facility consists of two opposing abutments of different sizes and a separate pier-group reaction frame adjacent to the larger abutment. The smaller abutment is backfilled with low-plasticity silt, and the larger abutment is backfilled with a clean sand. The supplemental facility consists of a pair of perpendicularly-oriented two-pile groups. Instrumentation of the abutment facility will include interface-pressure cells for measurement of backfill pressure on structural components, inclinometer casings to determine displacement profiles at various points within the soil and in selected piles, strain gages to record stress histories within the piles, and LVDT's, magnarules, and surveying targets to measure gross displacement of various points on the structure.

The load test program has been planned in three major phases. The first phase involves lateral load testing of the pile groups of the supplemental facility, and has recently been successfully completed. Results from this test phase will be used to isolate the contribution of the piles from the overall lateral behavior of the abutment system. The second phase of the test program will involve jacking horizontally between the two abutments using a pair of 200-ton rams positioned toward the outer edges of the abutments. The rams will be activated both individually and simultaneously to statically drive the abutments both longitudinally and in torsion about the vertical axis. Loading will be displacement controlled, and will provide two full cycles of each load combination. After forcing a pre-determined maximum level of cyclic displacement, an attempt will be made to establish the ultimate longitudinal capacity of the smaller abutment by statically driving it to "failure". The third and final testing phase will involve transverse loading of the larger abutment by jacking against the pier-group reaction frame.

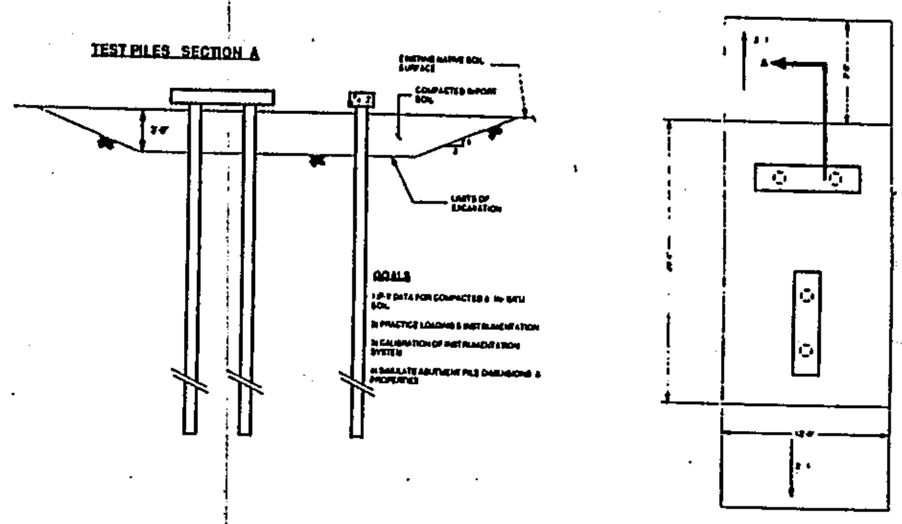
In addition to the field load-test program, 1/12-scale models of both the piles and abutments of the field-test facilities will be built and tested within the large centrifuge at UCD. Provided that test results can be achieved which are reasonably representative of the "near full scale" behavior, additional studies investigating a number of different design alternatives will be evaluated using centrifuge models.

8.5 Highway 280 Axial Load Tests [29]

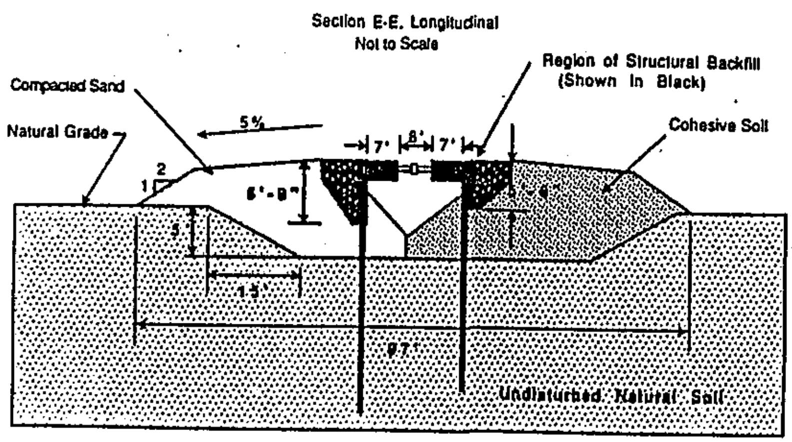
Caltrans has initiated a field load-test program targeted at an improved understanding of the tensile behavior of pile systems in soft clays. This research is motivated by more the stringent design requirements implemented since Loma Prieta for new and retrofitted bridge foundation systems to resist overturning moments. Current Caltrans designs require a tensile capacity of 200 kips at 1/2-inch deflection for each Class 100 pile. Prior to this time, Caltrans designs have conservatively assumed no tensile capacity could be developed within soft clays



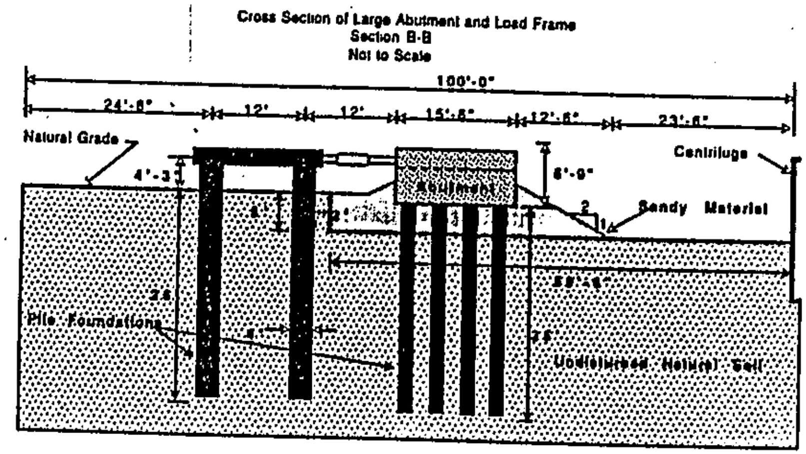
a) Plan of Primary Abutment Facility and Actuators



b) Plan and Section of Supplemental Pile Facility



c) Section thru Longitudinal Axis of Both Abutments



d) Section thru Large Abutment and Reaction Frame

Figure 10. General Layout of UC-Davis Facilities for Large-Scale Testing of Abutment Behavior.

such as the Bay Mud. The field test program will directly measure the tensile, as well as compressive capacity of several pile systems in a side-by-side comparison. At the time of this publication, all test piles have been installed, and testing is planned to begin within 1992.

A total of 28 piles representing 9 separate pile systems have been installed at a site below the Southern Freeway Viaduct (Hwy 280) near Evans Street. This site was chosen because of its unique subsurface profile which includes a 90-ft-thick layer of relatively uniform soft Bay Mud overlying a dense granular formation. These strata are overlain by a 20-ft-thick layer of miscellaneous fill. Two piles of each design were installed such that the tip elevation terminates within the Bay Mud. An additional pair of several of the designs were installed such that the tip is within the dense underlying strata. To avoid uncertainties associated with shaft friction in the miscellaneous surface fill, a casing of sufficient diameter to assure a clear space between the pile and fill was installed through the entire depth of fill at each test-pile location prior to pile installation.

Figure 11 illustrates the general site layout which involves alternating rows of test piles and reaction piles. All reaction piles are HP14x89 steel H-sections, and the test-pile systems include both five standard Caltrans designs and four newer proprietary systems. The standard designs are: 1) a 16-inch I.D. by 0.5-inch thick open-ended steel pipe pile, 2) a pre-loaded steel-pipe pile/tiedown system, 3) a HP14x89 steel H-pile, 4) a 14-inch square prestressed concrete pile, and 5) a timber pile. All standard designs were installed into the ground using conventional driving techniques except for the pile/tiedown system which involved both driving and a subsequent drilling/grouting operation. The proprietary designs are: 1) a tapered and fluted pile provided by Monotube Piling Co. which was driven using conventional methods, 2) a system provided by Fundex (Holland) which uses a pipe pile and a conical auger-flight tip which is first screwed into the ground and then followed by grout injection through the tip, 3) a pile/tiedown system provided by Nicholson Construction Co. which differs from the Caltrans pile/tiedown design primarily by the method of installation, and 4) a reinforced soil-grout column provided by Halliburton/Brown and Root which is installed using a specialized jet-grouting rig.

Load testing will be accomplished with the DNTMR 500-ton-capacity load frame which mounts atop of four reaction piles. All piles will be tested first in tension, then in compression. It is recognized that the compression-test results will be affected by prior tension testing, however, the tension results have been prioritized for this project. Each pile will be cycled through a series of progressively increasing load loops. Applied force will be measured with load cells and pile-head displacements will be measured relative to an independent reference frame using linear optical displacement gauges. Additionally, load-shedding behavior with depth will be documented during load application by recording either strain or displacement measurements (as appropriate to pile type) within the test piles at multiple depths. Pneumatic piezometers have been installed at three depths within

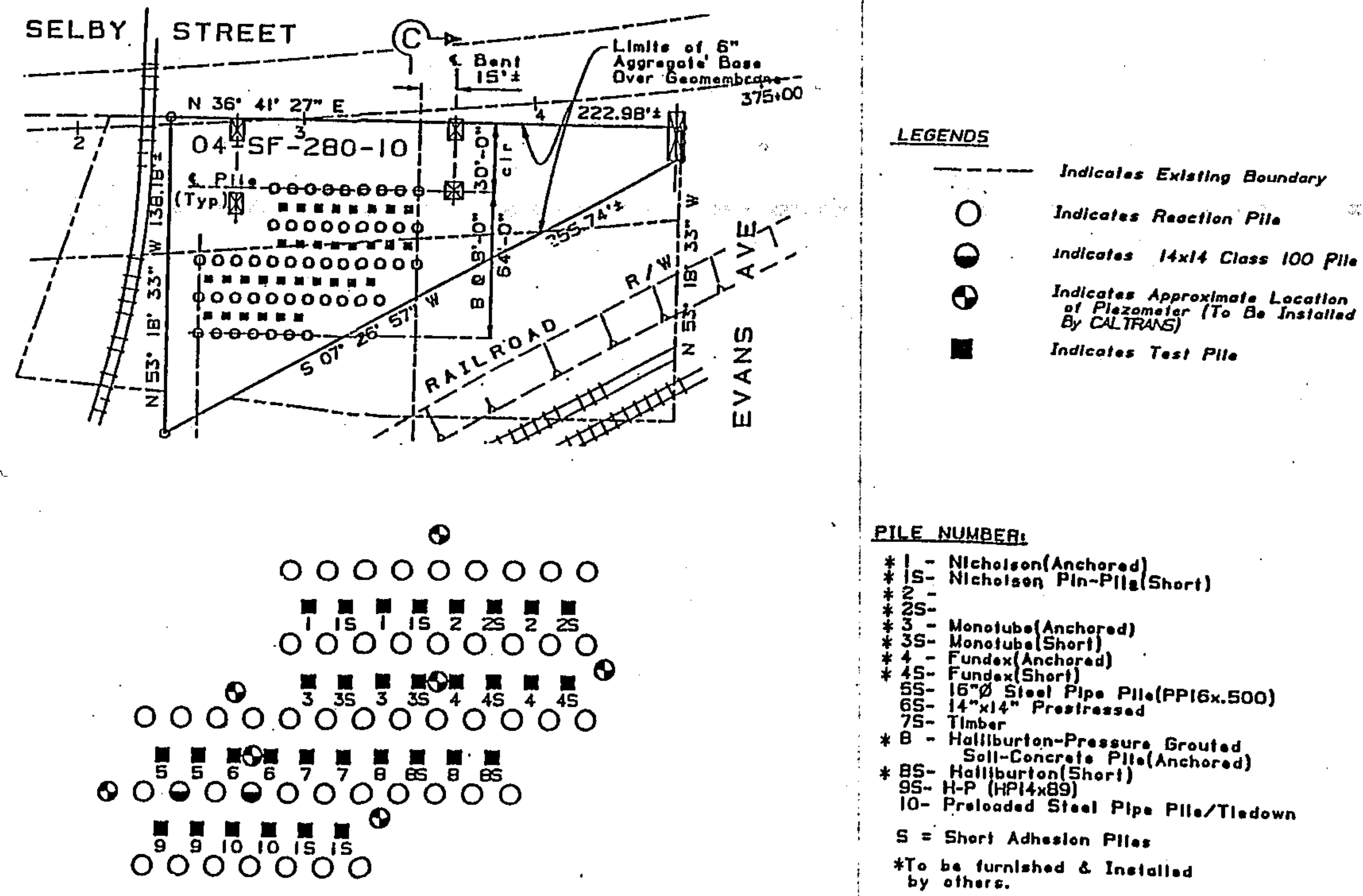


Figure 11. Location and General Layout of Highway 280 Pile Load Test Facility

the clay at each of four separate locations on the site to document regional pore-pressure fluctuations caused by both driving and testing operations. Finally, driving data (acceleration and stress) was recorded for all driven test-pile systems for both the final 30 to 40 feet of initial driving as well as during a subsequent re-strike.

Test results will yield both capacity and stiffness parameters for each of the pile systems being tested. Additionally, measured capacity results will be compared with predictions prepared on the basis of driving data. Finally, an overall evaluation of pile systems will be made which considers both economy and ease of installation in addition to capacity. Additional information on this project will be presented by Mason {62} at the Structures Congress at the UC-Irvine in April of 1993.

9. Conclusions

This paper has provided a current broad overview of the Caltrans-sponsored seismic foundation research program. The intent of this summary has been to provide the reader with both an abstract understanding of each of the individual projects, as well as a means to access more in-depth information on topics of particular interest. In addition to the projects discussed herein, an extensive research program is being conducted on purely structurally-related issues of seismic bridge design. These projects include a number of full-scale physical tests of both various structural components and alternative retrofit concepts as well as analytical studies. Considering the comprehensive scope of the Caltrans-sponsored seismic research program, the ~$5 million annual cost of continuing this aggressive effort is relatively low as it represents only ~10% of the current annual allocations for the retrofit of deficient structures, or ~2% of the current annual expenditures on new bridge construction. The problems associated with understanding the seismic behavior of the wide range of unique Caltrans structures spanning the unprecedented array of subsurface conditions which exist in California is indeed challenging. The continued dedication of research community in providing applications-oriented results will help Caltrans meet that challenge and assure both the efficiency and reliability of the California transportation system.

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