MOTEMS Strain-Based Seismic Evaluation of Wharf Structures Using ADINA

Hassan Sedarat, Tom Ballard, Alex Krimotat
SC Solutions, Inc.
1261 Oakmead Pkwy
Sunnyvale, California 94085

1. Introduction

Pursuant to Government Code 4526, The California States Lands Commission (CSLC) announced [1] its need for Engineering Consultants to perform a number of structural analyses with ADINA finite element program [2]. SC Solutions was selected to conduct this project for CSLC. As a part of this project, SC Solutions examined the MOTEMS [3] requirements applied to several typical pile-supported wharf structures using the ADINA finite element program. As per MOTEMS requirements, wharf structures can be modeled and analyzed using pushover analysis as well as time-history analysis. MOTEMS also allows detailed modeling of Soil-Structure Interaction (SSI) as well as using "point-of-fixity" approach to model the wharf. In this paper, the typical wharf structure that was defined by CSLC was modeled considering both detailed SSI modeling of the piles and the simplified approach with fixed-base. The two approaches were compared in this paper. The following six models were developed for detailed SSI and fixed-base models:

1. Reinforced concrete piles (detailed SSI and fixed-base models).
2. Pre-stressed piles (detailed SSI and fixed-base models).
3. Hollow steel piles (detailed SSI and fixed-base models).

The 475-year Contingency event (CLE) and the NEHRP Maximum Considered Earthquake (MCE) were considered for each model for the following analyses (total of 48 analyses).

1. Response spectrum analysis (CLE and MCE).
2. Pushover analysis in the transverse direction (CLE and MCE).
3. Pushover analysis in the longitudinal direction (CLE and MCE).
4. Nonlinear Dynamic analysis (CLE and MCE).

2. Geometry

The wharf geometry is shown in Figure 1. The Wharf structure is supported by six vertical piles spaced at 25-ft with 12.5-ft extension beyond the piles at each end. The concrete piles are 18-inch circular sections, whereas the hollow steel piles are 18-in external diameter and 1.25-inch thick. The piles are modeled with ADINA moment-curvature elements, which are distributed-plasticity elements with five integration points for each element. At elevations below the soil surface, the pile elements are connected to soil components in the transverse, longitudinal and vertical directions, in the detailed SSI model. The SSI system of pile and soil components is shown in Figure 2. Horizontal and vertical soil elements are plasticity-based truss elements. Therefore, there is no need to define explicit damping elements for soil because the radiation damping was not considered to be significant for this example problem in this site. Where radiation damping, representing the far-field effects, becomes important, it is recommended that the dashpot be connected in series with the soil stiffness to avoid unrealistically high dashpot forces [4].

In general, horizontal soil resistance for the upslope displacement is different from that of the down slope. Therefore, two soil trusses are needed in each direction. In this paper the soil surface was considered to be flat. Ground motions are defined in terms of displacement time history and are applied to the ground nodes of soil elements. In this paper only vertical piles support the slab.

Due to the lack of explicit definition of it, the interpretation of the fixed-base model was articulated to include the axial stiffness of piles and skin friction due to soil component. The suggested model in Figure 2 incorporates both axial stiffness of piles and skin friction in the fixed-base model.

3. Material

Nominal compressive strength of concrete piles is 5000 psi. Reinforcing steel bars have yield strength of 40 ksi. Effective pre-stressing stress is 1000 psi. Concrete cover is 3-inch. Hollow steel piles have yield strength of 60 ksi. All piles were modeled with the ADINA moment curvature elements. In calculation of moment-curvature of the sections, the expected strength factors for concrete and steel were 1.3 and 1.1, respectively. The cross-sections of typical piles are shown in Figure 3. The core of the concrete pile has typically more strength than the cover because of the confinement that the spirals provide. Depending on the amount of confinement in the pile, concrete properties were computed from Mander's equations [5]. For the pre-stressed pile the top portion of the pile was not considered pre-stressed to take into account the development length of the pre-stressing strands. Typical Moment-curvature relations for the reinforced concrete pile, pre-stressed pile, and hollow steel pile are shown in Figure 3. The axial force-curvature surfaces for each pile are presented in the same Figures. These yield surfaces are used to compute strains in the concrete, reinforcement bars, strands, and steel section. The moment-curvature relations and the yield surfaces for piles were obtained using the program SPEMC [6].

4. Input Ground Motion

Horizontal ground motions are applied at the ground node of each soil element. The design spectra of the motion are shown in Figure 4. The displacement time-histories for the CLE event are presented in the same Figure. The recommendation of the geotechnical engineer for this project was that the MCE event be 1.35 times the CLE (see Acknowledgement).

5. Strain Limits

Strain limits in this work are based on MOTEMS level 2 acceptance criteria. For this level, maximum concrete compression strain above soil is 0.025, while it is limited to 0.008 for the in-ground regions. Maximum reinforcing steel tension strain is 0.05. Maximum pre-stressing steel tension strain is 0.04.

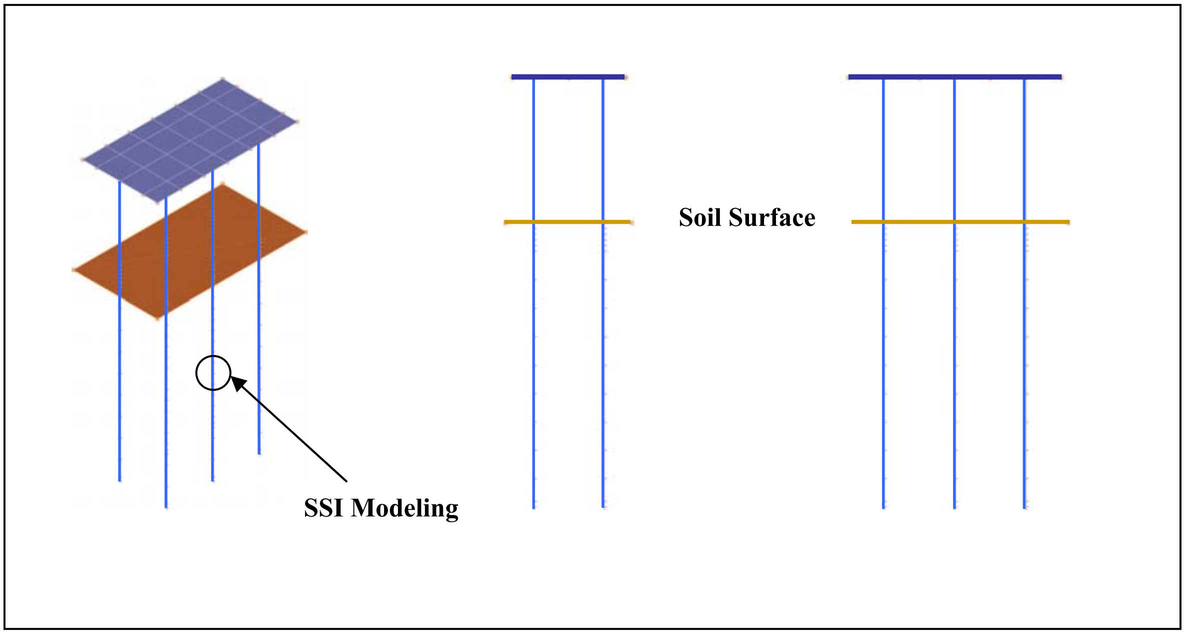


Figure 1: Geometry of the

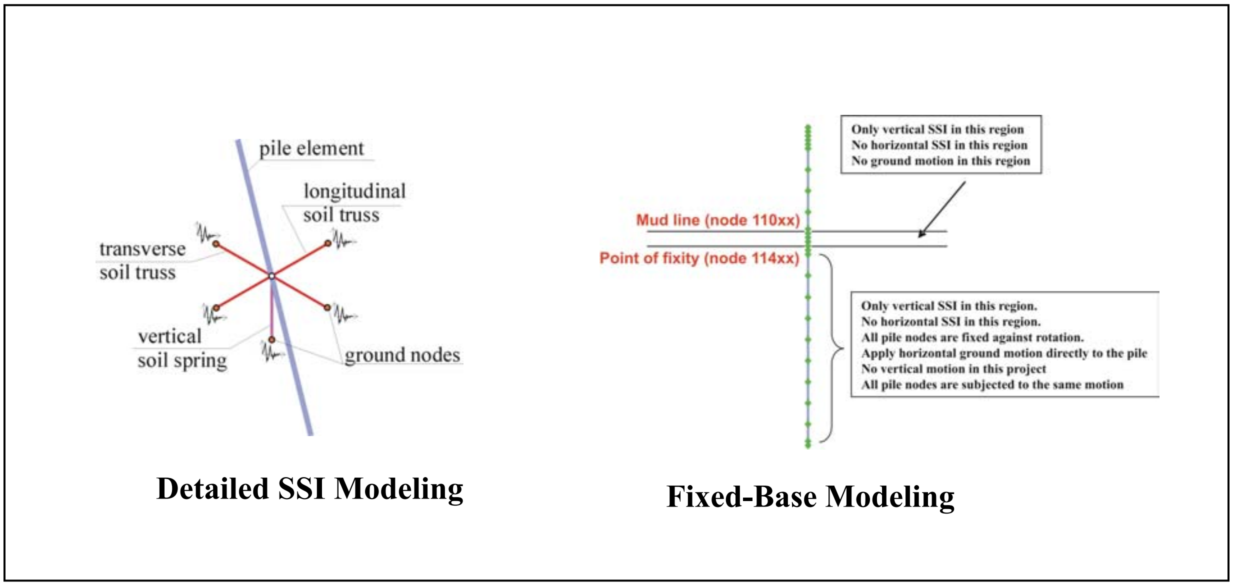
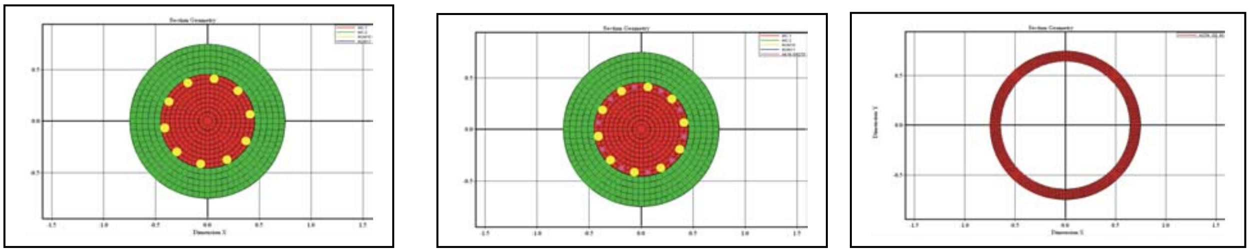
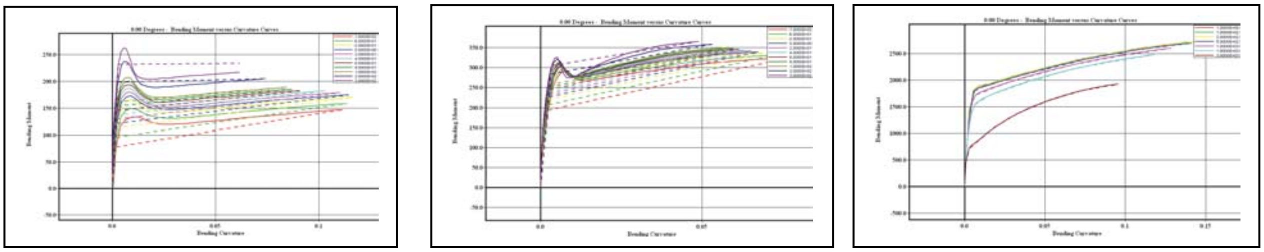


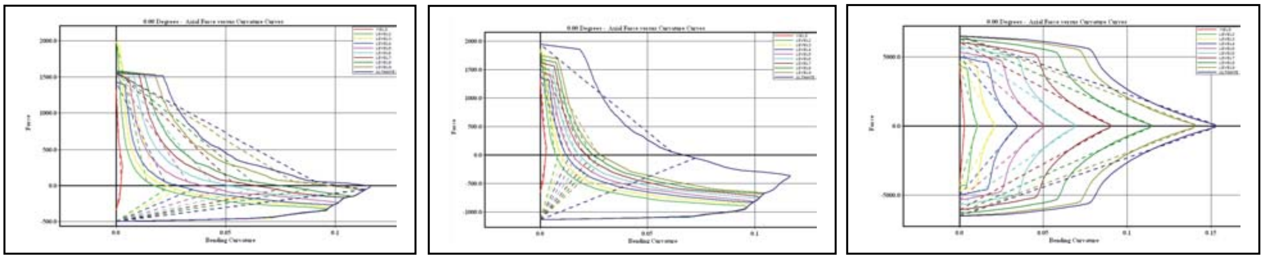
Figure 2: SSI Modeling



a. Cross-Section



b. Moment-Curvature Relations



c. Axial Force-Curvature Yield Surface

Figure 3: Typical Cross-Section, Moment-Curvature, and Yield Surface

6. Response Spectrum Analysis – Target Displacements

For irregular structures, MOTEMS requires that the target displacement be computed by a response spectrum analysis. Although, the structure in this paper is not irregular, almost all wharf structures are. Therefore, using the MOTEMS simplified equation to compute target displacement instead of response spectrum analysis would have jeopardized the generality of this work.

MOTEMS further stipulates that in the response spectrum analysis linear elastic material should be used to model soil components. The material of these elastic elements shall be based on soil secant stiffness. The piles need to be defined with their cracked sectional properties. The piles were modeled with ADINA moment-curvature elements. Therefore, the initial stiffness of the moment-curvature relation will be used in the frequency analysis, which is a realistic representation of the cracked section, provided that the moment-curvature relations were idealized properly. The value of target displacement depends on the period of structure. The period of each model is summarized in Table 1. Unlike the wharf structures that usually have numerous piles in the longitudinal and in the transverse directions, the torsional rigidity of this system is low. Therefore, the first mode of vibration is always torsion. The second and third modes are translation with almost 90% of effective modal mass. The vertical mode is mode 17, which is a little shy of 90% of mass. The target displacements of the three models vary from 2.2 to 2.3 ft for a CLE event and from 2.97 to 3.09 ft for a MCE event.

7. Pushover Analysis

If the response of a structure is mostly controlled by a single mode, then the use of pushover analysis could be justified to estimate the nonlinear behavior of structures. However, wharf structures in general are not symmetrical. In most cases there is no one single mode that could capture even 75% of the effective modal mass of the structure. Therefore, when using pushover analysis for structures of this nature, the following questions should be taken into consideration: How to push the structure in the transverse and in the longitudinal directions? Should it be concurrent push or independent pushover analyses? How to combine deformations resulted from pushover analyses?

ATC-33 [7] requires that as a minimum, analysis shall be performed with lateral loads applied independently in two principal directions. It further states that "explicit consideration of concurrent loading in two orthogonal directions is not required, except for force-controlled actions which shall be computed by combining 100% of the action in one direction with 30% of the actions in the orthogonal direction. However, in the capacity/demand assessment of deformation-controlled actions it should be considered that orthogonality effects exist and that the building is expected to sustain deformations simultaneously in the orthogonal directions". This means that the deformation-controlled actions should be directly added from two orthogonal pushover analyses (100% rule). In this paper we compute the strain values based on 100% rule and then compare them with an SRSS combination method. It will be shown that, in general, SRSS combination method for total strain calculation provides smaller values than the 100%. The authors of this paper recommend that the 100% rule, as is defined by ATC-33, is a more appropriate method of combining strains for a pushover analysis.

Pushover analysis was performed for reinforced concrete, pre-stressed concrete and steel hollow piles. For each of them a detailed SSI model and a fixed-base model were considered. A typical transverse pushover curve is shown in Figure 5. In this Figure steel and concrete strain histories are also plotted with MOTEMS target displacements marked on them. In this way the strains for each pile were extracted at the MOTEMS target displacement. The pushover analysis was repeated for the longitudinal direction and the strains from the two analyses were combined by 100% rule and SRSS rule as discussed earlier. The strains are compared with the acceptable values and the strain D/C values are tabulated in Table 2.

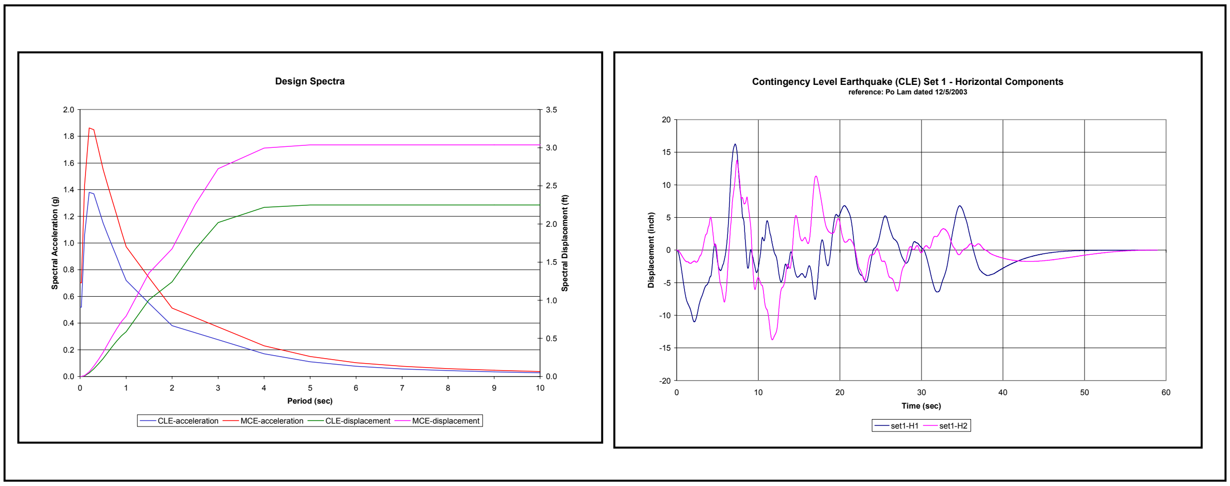


Figure 4: Input Ground Motion

	Reinforced Concrete Pile		Pre-stressed Pile		Hollow Steel Pile	
	Detailed SSI	fixed- base	Detailed SSI	fixed- base	Detailed SSI	fixed- base
Mode	Period (sec)	Period (sec)	Period (sec)	Period (sec)	Period (sec)	Period (sec)
1	7.5063	7.8170	6.8850	7.3020	3.2160	3.5140
2	7.1900	7.4890	6.5840	6.9810	3.0890	3.3730
3	7.1829	7.4810	6.5760	6.9740	3.0770	3.3610
4	0.3018	0.3165	0.2771	0.2972	0.1794	0.1794
5	0.3016	0.3163	0.2765	0.2966	0.1692	0.1696
6	0.3015	0.3162	0.2763	0.2964	0.1538	0.1557
7	0.3014	0.3161	0.2763	0.2965	0.1423	0.1454
8	0.3001	0.3144	0.2762	0.2963	0.1300	0.1398
9	0.2993	0.3137	0.2760	0.2962	0.1228	0.1364
10	0.2992	0.3135	0.2760	0.2961	0.1227	0.1364
11	0.2992	0.3135	0.2760	0.2961	0.1225	0.1362
12	0.2991	0.3134	0.2759	0.2960	0.1222	0.1359
13	0.2986	0.3128	0.2757	0.2955	0.1219	0.1356
14	0.2984	0.3125	0.2751	0.2949	0.1217	0.1354
15	0.2976	0.3118	0.2744	0.2944	0.1217	0.1354
16	0.2060	0.2060	0.2057	0.2051	0.1212	0.1348
17	0.1917	0.1917	0.1916	0.1910	0.1204	0.1337
18	0.1800	0.1801	0.1797	0.1792	0.1188	0.1303
19	0.1593	0.1594	0.1590	0.1589	0.1181	0.1280
20	0.1333	0.1334	0.1330	0.1329	0.1141	0.1180
99	0.0162	0.0142	0.0141	0.0142	0.0129	0.0123
100	0.0162	0.0141	0.0135	0.0141	0.0129	0.0123

Table 1: Period of Vibration

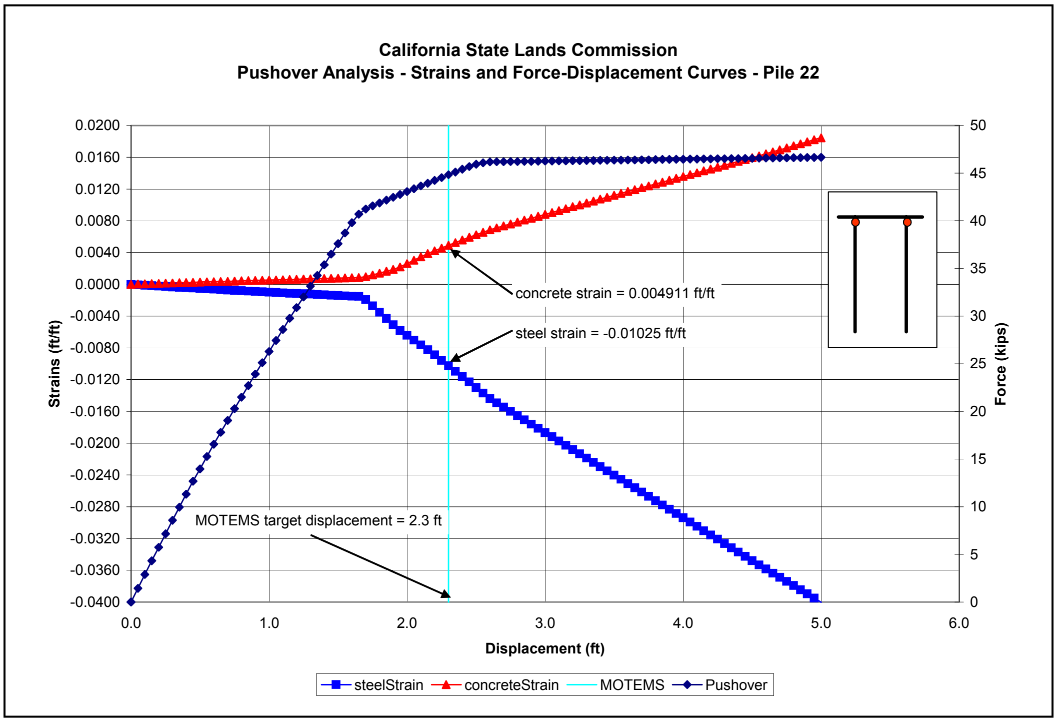


Figure 5: Typical Pushover Curve and Strain Values
Reinforced Concrete with Detailed SSI

8. Time-History Analysis

In a time-history analysis with detailed SSI modeling, the ground motions are applied at the ground nodes of each soil elements in the longitudinal, vertical and transverse directions. In general, each of these motions is different from each other, because as seismic waves move in the longitudinal direction or along the height of the pile in the vertical direction the soil properties change the wave characteristics. Therefore, time-history analysis of a wharf structure is a multiple-support excitation not only along the length of the wharf, but also along the height of the piles. The authors of this paper believe that this approach provides more reliable estimate of the response of the structure than the pushover analysis. Although the fixed-base model is an approximation of the problem, it is often used in practice. In this paper time-history analyses for this case were also conducted and compared with that of the detailed SSI model.

The requirement that “a time-history analysis should always be compared with pushover analysis to ensure that the results are reasonable” is achievable. However, it is a subjective requirement especially if the structure is not regular then it is very difficult to correlate the results obtained from time-history analysis with those obtained from pushover analysis. On the other hand, the requirement that “displacements calculated from the nonlinear analysis may be used directly for the design, but shall not be less than 80% of the values obtained from pushover analysis” is not clear. In a time-history analysis total displacements are computed, whereas in a pushover analysis displacements are computed with respect to the fixed ground nodes. Since in a time-history analysis more than a single ground motion is applied to the structure, it is not clear what the point of reference is for this requirement.

The strain time-histories for steel and concrete were extracted for each model and are presented for a typical case in Figure 6. In the same Figure the total displacements at the center line of the slab are plotted. The maximum strain values are compared with the acceptable strains and the strain D/C are summarized in Table 2.

Figure 7 presents the steel and concrete strains D/C along the length of a typical pile when modeled with detailed SSI procedure. In this Figure the strain D/C values from pushover analyses (100% rule and SRSS) are compared with those of time-history analysis. Figure 8 illustrates the strain D/C along the length of a typical pile for the fixed- base model. The immediate conclusion from these two Figures is that the fixed-base model provides a different distribution of damage along the height of the pile. Table 2 also indicates that in the fixed-base model the reinforced concrete pile is overly stressed at the base. Note that the in-ground acceptable concrete strain is much smaller than that above the soil. Therefore, the SSI detailed model shows an increase in strain D/C in the vicinity of soil surface, as it was expected. However, the top of the pile is still the most critical section. On other hand the fixed-base model directs engineer to a design that the section at the point-of-fixity is the most critical one. For the reinforced concrete pile, strain D/C values are smaller when detailed SSI model is used, whereas they are larger when fixed-base model is used (Table 2). The SRSS rule provides smaller strain D/C than those obtained from 100% rule (Table 2). The fixed-base model provides large strain D/C values at the point-of-fixity, whereas the detailed SSI model shows that strain D/C are larger at the top of the pile (Figure 7 and Figure 8).

9. Conclusions

The current state of practice for seismic evaluation of wharf structures is based on pushover analysis of a simplified model that approximate the behavior of a three-dimensional wharf structures. In this paper, MOTEMS requirements were applied to several typical pile-supported wharf structures using the ADINA finite element program. The various MOTEMS methods for evaluation of these structures for earthquake ground motions were investigated and compared. A simplified model was developed and its responses were compared with those of a three-dimensional model of wharf structure that contained detailed modeling of soil-structure-interaction. Pushover analyses in the transverse and longitudinal directions were conducted, as per MOTEMS requirements. The results obtained from the pushover analyses were compared with those obtained from nonlinear dynamic analyses. The conclusions that can be drawn from this study are summarized below.

1. It is important that proper analysis methods, specified by MOTEMS are selected. This selection must be based on the type of structure, soil conditions, and proximity to the fault. Also, understanding of the nonlinear behavior of structures under investigation is an essential part of the development of the proper analysis strategy. Since strain limits are defined for steel and concrete at various performance limits that corresponds to the various seismic events with their associated levels of risk, the analysis strategy should be consistent with the process of recovery of those quantities.
2. The concept of pushover analysis is based on a single-degree-of-freedom system. When the structure has many degrees-of-freedom with inherent unsymmetrical features in both geometry and materials, it will become hard to justify the applicability of this concept. Wharf structures have unsymmetrical geometry. The strength of soil toward sea is different than that toward the land. Also, since the wharf structures are usually long the soil properties can vary significantly from one end to the other. Therefore, application of pushover analysis to these structures has to be used with caution.
3. In a pushover analysis, the direction of the push, method of push, and combination of the force-controlled actions and deformation-controlled actions should be considered.
4. When wharfs are modeled with fixed-base at the point-of-fixity, it is important, as a minimum, to capture the axial stiffness of the pile and the skin friction of the soil component.

10. Acknowledgments

Financial support for this investigation was provided by the California States Lands Commissions. The authors would like to express their gratitude to Mr. Martin Eskijan, P.E. at the California States Lands Commissions. The efforts of Dr. Po Lam from Earth Mechanics who developed the soil properties and ground motions are greatly appreciated.

11. References

1. California States of Lands Commission, 100 Howe Ave, Suite 100South, Sacramento, CA 95825, Bid Log Number 2003-10, Title: Engineering Consultant, August 28, 2003.
2. Automatic Dynamic Incremental Nonlinear Analysis, ADINA, ADINA R&D, Inc. 71 Eltin Avenue, Watertown, MA 02172.
3. Marine Oil Terminal Engineering and Maintenance Standards (MOTEMS), California States Lands Commissions, 2003.
4. Shaomin Wang, Bruce L. Kutter, M. Jacob Chacko, Daniel Wilson, Ross w. Boulanger, Abbas Abghari, "Nonlinear Seismic Soil-Pile Structure Interaction", Earthquake Spectra, Volume 14, No. 2, May 1998.
5. Mander J.B., Priestly, M.J.N., and Park, R., "Theoretical Stress-Strain Model for Confined Concrete", Journal of Structural Division, ASCE, Vol. 114, No 8, August 1988.
6. Thomas Ballards, P.E., SPEMC - an in-house ADINA-oriented tool developed for the computation of moment-curvature and yield surfaces for arbitrary sections.
7. ATC-33.03 – Guidelines for the Seismic Rehabilitation of Buildings, Advanced Technology Council October 1995.

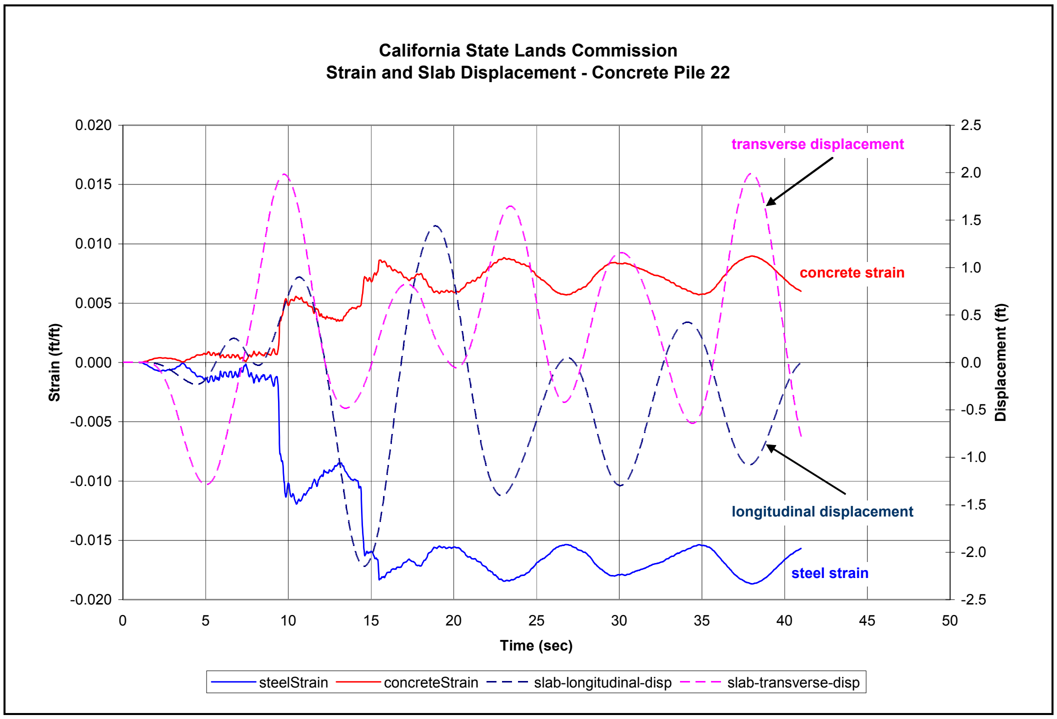


Figure 6: Typical Time-History of the Response Displacement and Strain Reinforced Concrete with Detailed SSI

CLE Event

	time-history		push with 100% rule		push with SRSS rule	
	steel	conc.	steel	conc.	steel	conc.
Reinforced Concrete Detailed SSI	0.43	0.37	0.47	0.39	0.33	0.28
Reinforced Concrete Fixed-Base	0.53	1.46	0.40	1.03	0.29	0.73
Pre-Stress Detailed SSI	0.54	0.38	0.80	0.53	0.56	0.38
Pre-Stress Fixed-Base	0.61	0.39	0.85	0.57	0.60	0.40
Hollow Steel Detailed SSI	0.16	0.17	0.17	0.18	0.12	0.13
Hollow Steel Fixed-Base	0.20	0.23	0.21	0.24	0.15	0.17

MCE Event

	time-history		push with 100% rule		push with SRSS rule	
	steel	conc.	steel	conc.	steel	conc.
Reinforced Concrete Detailed SSI	0.73	0.65	0.84	0.88	0.59	0.62
Reinforced Concrete Fixed-Base	0.78	2.18	0.72	2.03	0.51	1.44
Pre-Stress Detailed SSI	0.83	0.58	1.37	0.93	0.97	0.66
Pre-Stress Fixed-Base	0.65	0.54	1.06	0.95	0.75	0.67
Hollow Steel Detailed SSI	0.24	0.26	0.28	0.30	0.20	0.21
Hollow Steel Fixed-Base	0.92	1.11	0.34	0.36	0.24	0.26

Table 2: Summary of Strain D/C Values

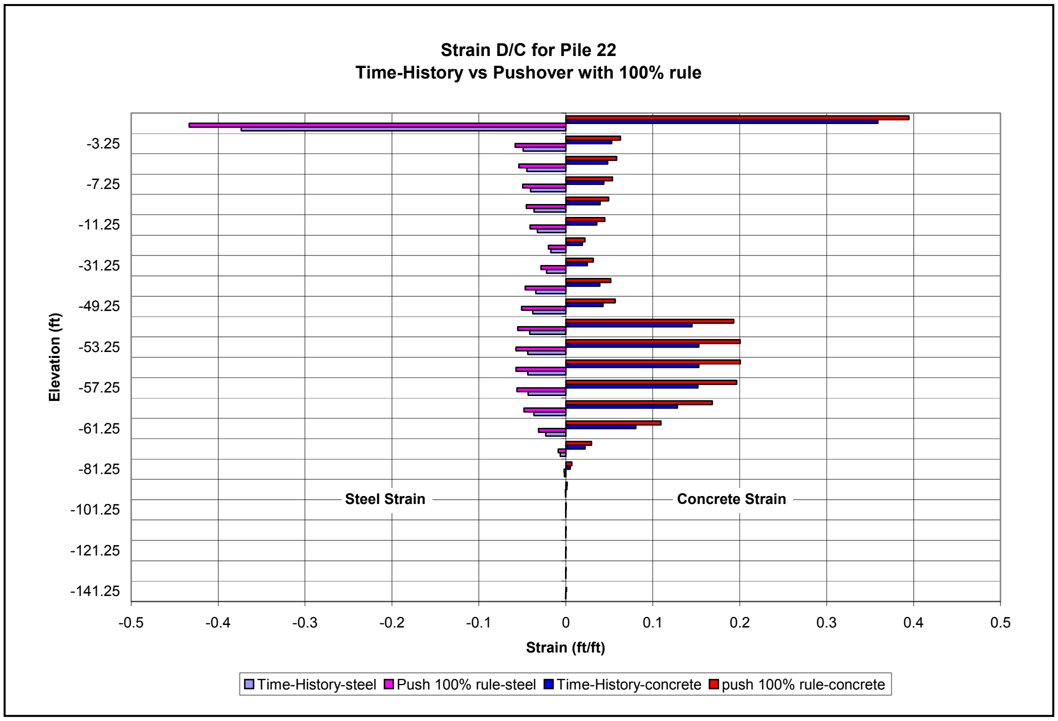


Figure 7: Strain D/C of Typical Reinforced Concrete under CLE – Detailed SSI Model

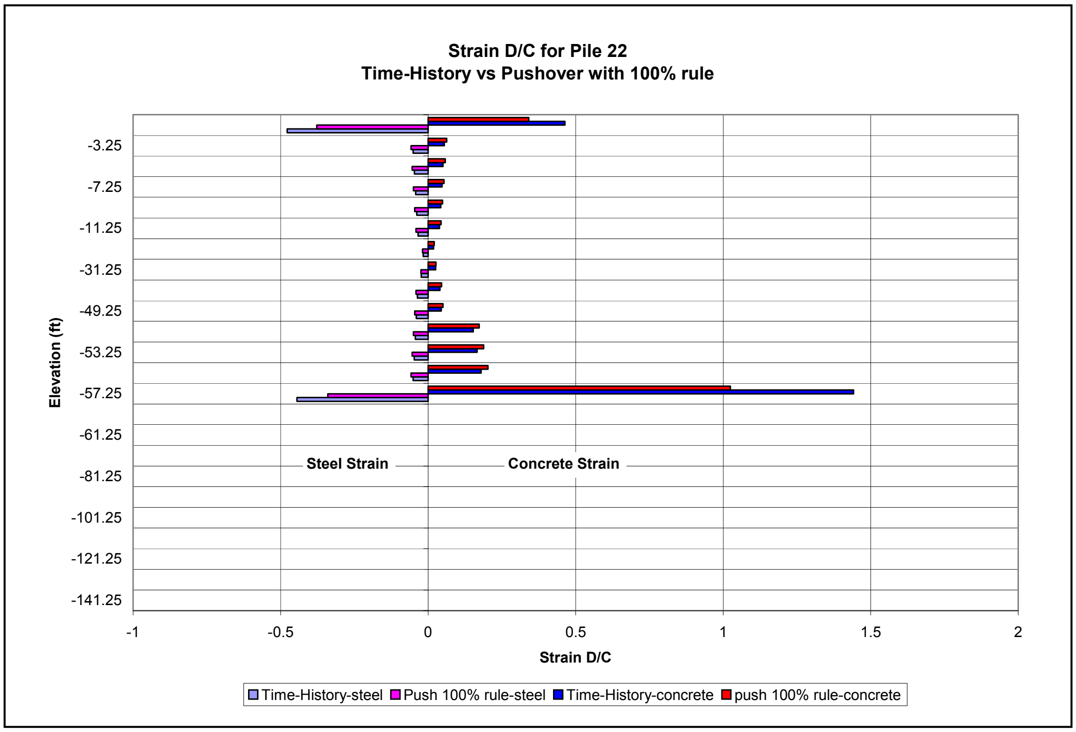


Figure 8: Strain D/C of Typical Reinforced Concrete under CLE – Fixed-Base Model