EVALUATION OF SEISMIC LATERAL PILE CAPACITY
MARK CLARK EXPRESSWAY
CHARLESTON, SOUTH CAROLINA

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Abstract

Subsurface exploration for the Mark Clark Expressway revealed soil profiles that ranged from stiff soils to deep deposits of soft underconsolidated dredge spoils. A simplified procedure was developed to predict the lateral load-deflection characteristics of single piling under seismic loading. The subgrade land-deflection curves are modified based on both conventional static load-deflection (P-Y) relationships and the reduction of modulus due to cyclic strains defined by free field motions. A sample problem is presented to illustrate application of the propose method.

Introduction

During a seismic event, the maximum lateral superstructure loads are transferred to a deep foundation at the same time that significant seismic strains are occurring within the subgrade. Individual piling experience cyclic strains induced by the superstructure seismic base shear forces and the differential movement of subgrade layers. The subgrade soils adjacent to the piling are subjected to this same combination of strains. Soils subjected to significant strains experience a degradation of modulus and, thus, provide a diminishing resistance to the seismic lateral forces. Unfortunately, this reduction in resistance occurs simultaneously with the maximum lateral superstructure forces. The general mechanism for soil-pile interaction during seismic loading is shown on Figure 1[(1)]. At shallow depths, the bending movements within the piling are dominated by strains generated by the superstructure lateral forces. At greater depths, the movements within the piling are dominated by those induced by earthquake displacement of the subgrade.

Subsurface exploration along the route of the proposed expressway generally indicated 15 to 40 feet of sands and silts overlying a consolidated, fine grained, marine deposit known as Cooper Marl. The Cooper Marl provides support for most deep foundations in this region and this became particularly true for the large loads associated with this project.

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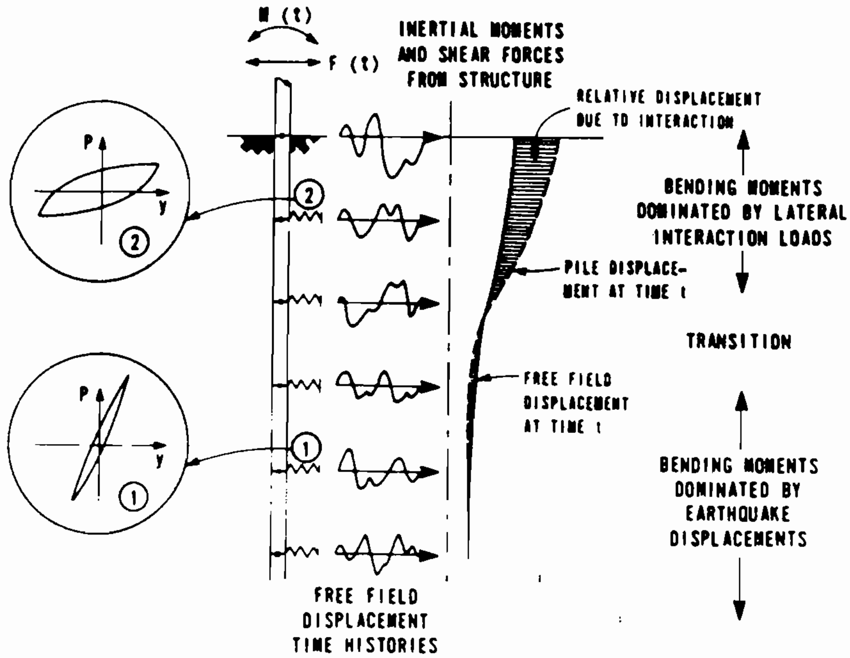

Figure 1 Seismic Soil - Pile Interaction

However, subsurface exploration of the dredged material Spoil Island adjacent to the Cooper River and along the bridge alignment reveals unique subgrade conditions that complicate development of lateral capacity in deep foundations. The soil profile is shown on Figure 2[2]. A thick layer of underconsolidated sediments and dredge spoils overly the Cooper Marl offers little lateral resistance to pile movements. Typical properties and descriptions of the four significant soil types found in this profile are given in Table 1. Subgrade coefficients for static lateral pile analysis are given. These same sediments have the potential for generation of significant down-drag forces on piles due to the on-going consolidation of this material. Battered piles exacerbate the influence of the down-drag forces and have, therefore, been eliminated from consideration within this region. This paper presents the development of lateral load deflection criteria for vertical piling placed within this region.

SEISMIC SOIL LAYER RESPONSE

The Spoil Island soil profile selected for this study was subjected to the synthetic seismic motions using two layered system computer analysis programs LEVSFC[3] and SHAKE[4]. Both programs model the response of a horizontally layered system to the vertical propagation of pure shear waves. Fortunately, the limited topographic relief of the Charleston region is ideally suited for such a simulation. The two programs differ somewhat in their solution technique, with the LEVSFC program using a lumped mass simulation and modal analysis in the time domain and the SHAKE simulation using a direct integration of the differential equations of motion in the frequency domain.

TABLE 1 SOIL PROPERTIES

	STATIC					DYNAMIC		
SOIL TYPE	FRICTION ANGLE	COHESION ksf	UNIT WT. ksf	SUBGRADE[(1)] COEFFICIENT	INDEX[(1)] r	FREE-FIELD[(2)] DYNAMIC STRAIN	FREE-FIELD[(3)] MODULUS RF	LOAD HISTORY[(4)] MODULUS RF
I	30	0	.110	50	1	0.10	.28	1.0
II	0	2.55	107	650	0	0.01	.45	1.0
III	0	.25	.09	2	1	1.00	.05	0.8
IV	0	1.0	.12	100	0	0.03	.35	1.0

DESCRIPTION:
- I Very loose to fim sility stands and clayey silts
- II Cooper Marl
- III Very soft to soft clays and silts
- IV Firm to stiff clays and silts

FOOTNOTES:

(1) Modulus of subgrade reaction = K = $\frac{\text{Subgrade Coefficient}}{\text{Pile Diameter}} (Z)^r$

where Z = depth below ground surface.

(2) 0.65 x maximum strain obtained from layered system analysis.

(3) Per Reference (3)

(4) Per Figure 7 using eight load cycles.

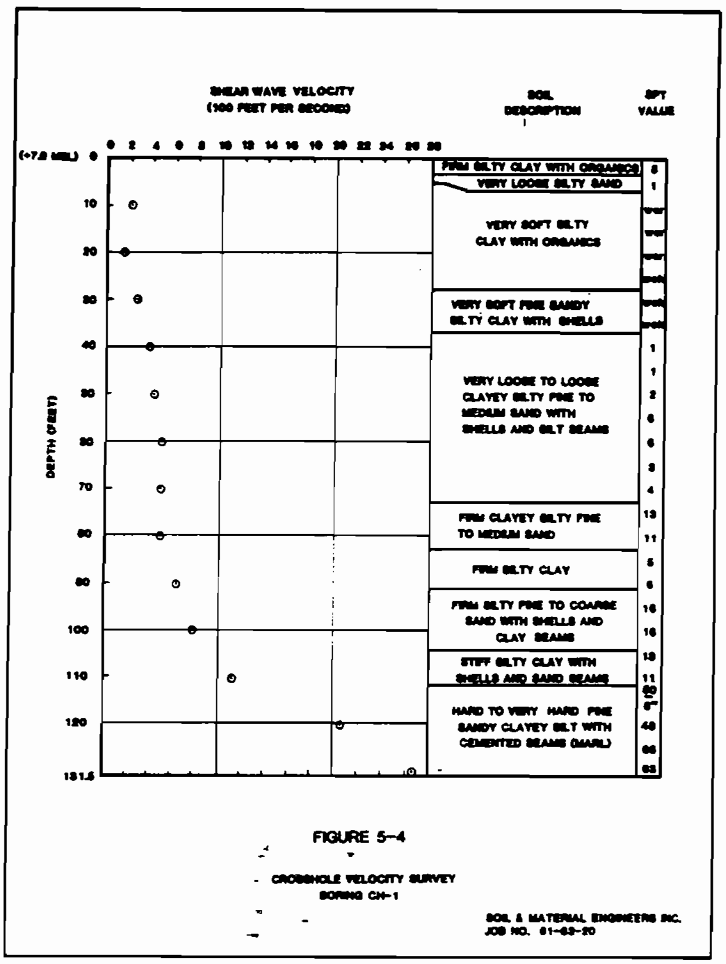

Figure 2 Soil Profile

Spoil Island

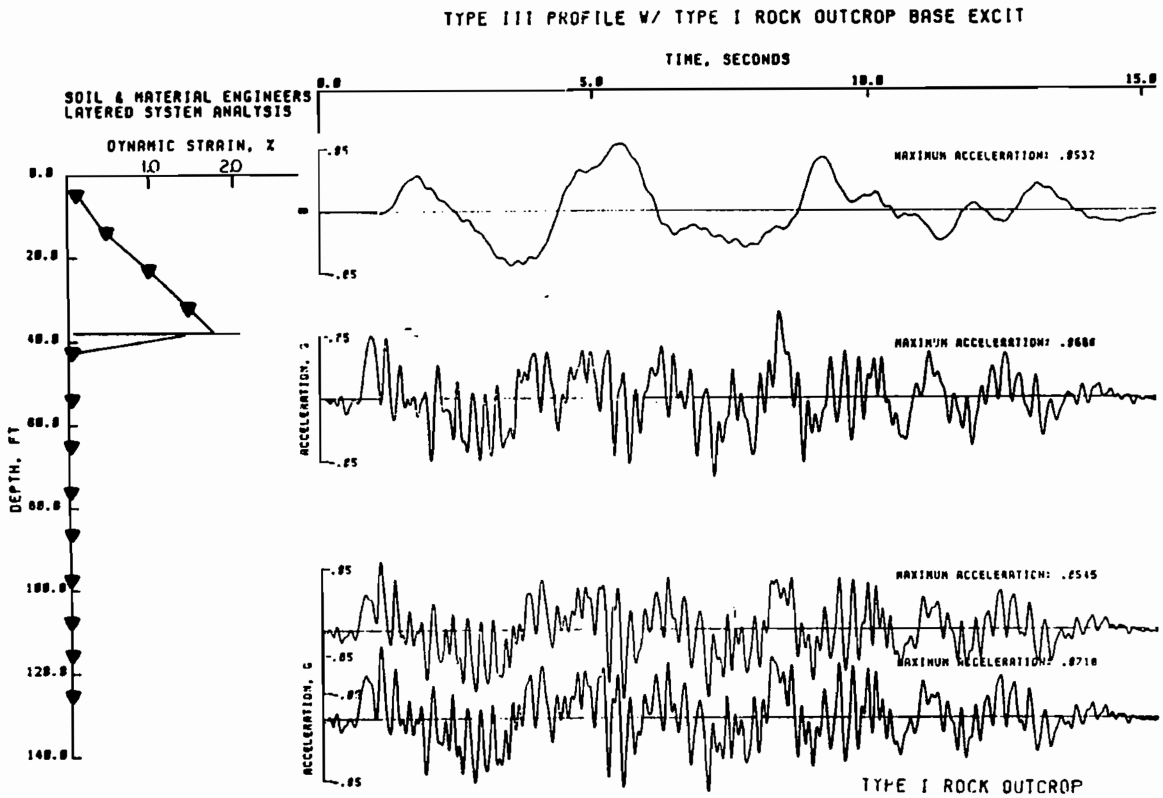

Figure 3 Shake Analysis - Spoil Island

An initial evaluation was performed using SHAKE with the synthetic earthquake ground surface motions applied to the surface of each respective soil profile. An analysis was attempted with SHAKE using a design earthquake developed for ATC-6 Type III soil profile applied to the surface of the Naval Spoil Island profile. This solution "blew up" numerically and indicated accelerations in the marl orders of magnitude beyond reason. An alternate technique was used to generate an estimate of the theoretical rock outcrop motion generated by the application of an ATC-6 Type I design motion to a typical inland site and then transfer of this rock motion to the base of the Naval Spoil Island profile. The results of this analysis are shown on Figure 3. The bedrock motion beneath the Spoil Island profile had a peak acceleration of 0.045g. Dynamic strains within the Spoil Island profile are surprisingly small (less than 0.02%) except in the upper 40 feet. Means dynamic strains, defined as 0.65 x peak strain, are given in Table 1 for each of the four soil types for the 100 year design event. The high frequency filtering by the Spoil Island profile is quite dramatic as shown by the nearly harmonic motion at the ground surface.

The amplification or attenuation of the base motion by the Spoil Island profile for bedrock motions of varying peak acceleration is shown on Figure 4. The Spoil Island profile is exceptional in that it was not possible to achieve greater than 0.1g acceleration at the ground surface regardless of the peak acceleration used at the base. This was true using both bedrock and scaled Type I and III base motions.

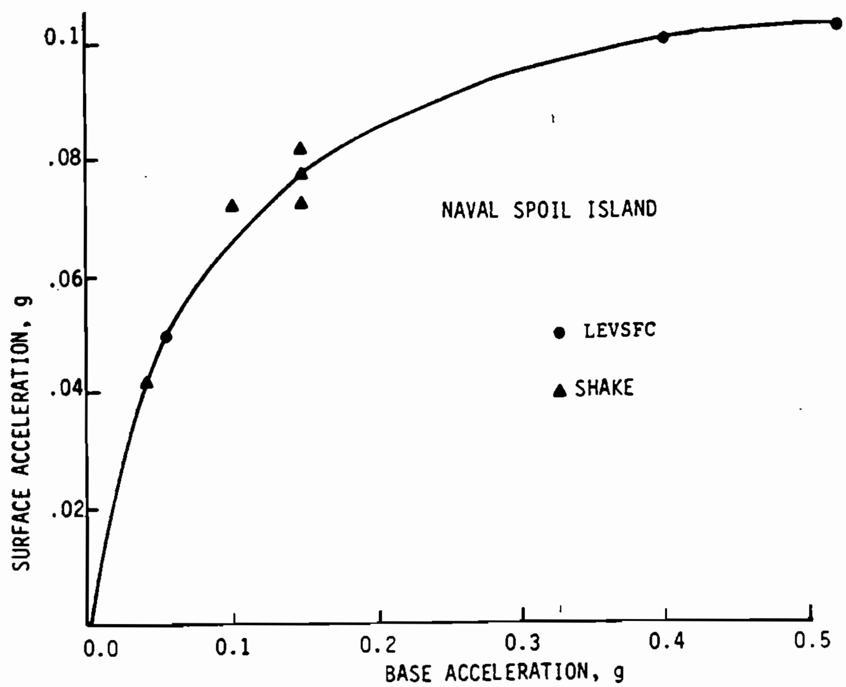

Figure 4 Amplification - Spoil Island

Dynamic displacements generated in the soil profiles during a seismic event are important considerations in the design of deep foundations penetrating these layers. The piles must generally be designed to survive the deformations imposed by the movement of the adjacent soil and the soil itself will have its modulus influenced by both the level and number of strain cycles it experiences during the event. Contours of peak dynamic displacement that occur during these simulated earthquakes are shown in Figure 5. Note that significant displacement is limited to the weaker near surface layers. Peak dynamic strains generated within the soil layers are shown on Figure 6.

The most significant cyclic strains will occur in the near surface organic silty clays that have standard penetration resistances of weight of hammer (WOH) or weight or rod (WOR). These deposits are underconsolidated and displayed extremely low shear strengths(2). However, these sediments do appear to maintain approximately half of this strength even in a completely remolded condition. The distribution of dynamic strains during free-field seismic excitation of this layer are shown on Figure 3 and are somewhat surprising. The maximum strain (1.5%) occurs at the base of this layer and decreases to a minimum value (.5%) near surface. It is reasonable to anticipate that dynamic strains induced by deflection of the piling by superstructure loads will be inverse to this, that is they will be largest at the ground surface and decrease with depth. Thus, a combination of both strain envelopes may yield a fairly uniform distribution of peak dynamic strains throughout the layer.

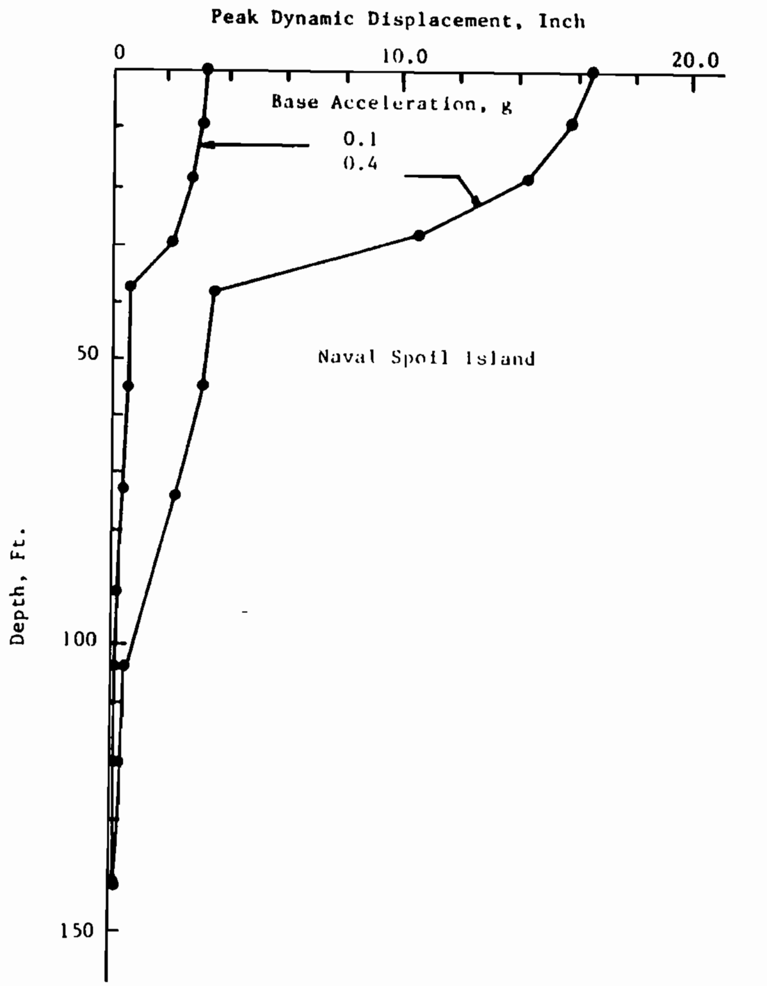

Figure 5 Peak Dynamic Displacements

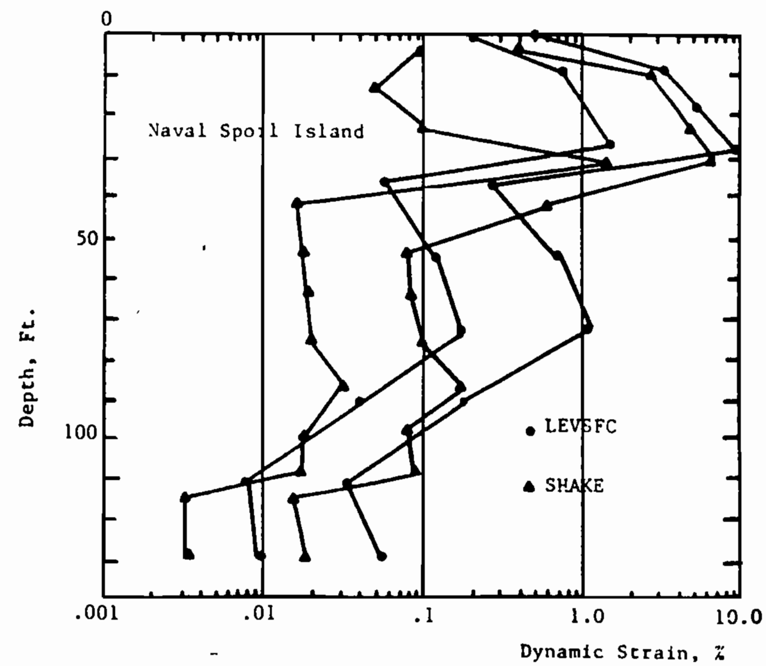

Figure 6 Peak Dynamic Strains

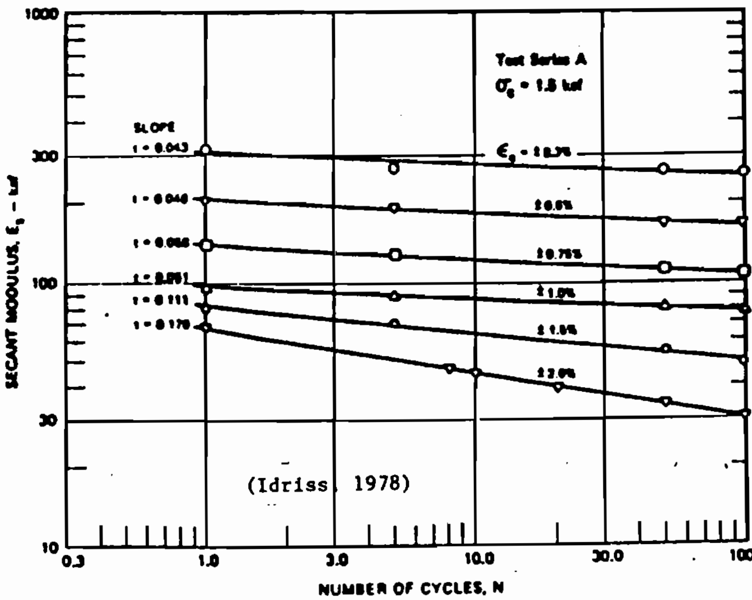

Figure 7 Soil Modulus vs. Stress History

SUBGRADE SOIL PROPERTIES

The layered system analyses incorporate in situ measured shear wave velocities to provide a measure of subgrade modulus values at low strain (.0001%) amplitudes. A soil modulus reduction relationships for both sands and clays[3] based on dynamic strain levels are incorporated in the analyses. These modulus reduction relationships are independent of loading history.

In addition to the amplitude of dynamic strain, the modulus of a soil can be influenced by its stress history. The degradation of the modulus of clays is influenced by both the number and the amplitude of stress cycles in its recent history. Such a relationship is shown on Figure 7 for a marine sediment having physical properties similar to clayey soils in the Spoil Island. Note that the cyclic reduction in modulus does not become significant until the dynamic strains exceed 1%. Similar cyclic load tests performed on sands[5] indicate that the number of load cycles does not influence the modulus reduction of sands. Additional research[6] on the cyclic response of clays indicates that a threshold level of strain must be exceeded before cyclic deformations (or strains) become significant. For most clays, this threshold of deformation occurs at strain levels between 0.001 to 0.01%. Based on dynamic strain levels obtained from layered system analyses, the peak dynamic strains in the spoil area will exceed this threshold.

Dynamic free-field displacements in the Spoil Island were obtained by double integration of the acceleration time histories obtained from the layered system analyses and are plotted on Figure 8. The resulting time histories indicate that four load reversal cycles will be generated by the 100-year design event. However, it is generally recommended[13] that earthquakes of this magnitude by designed assuming 8 load cycles. Modulus reduction factors based on 8 load cycles and using the limited empirical data given in Figure 7 are presented in Table 1 for the four soils that make up the Spoil Island Profile.

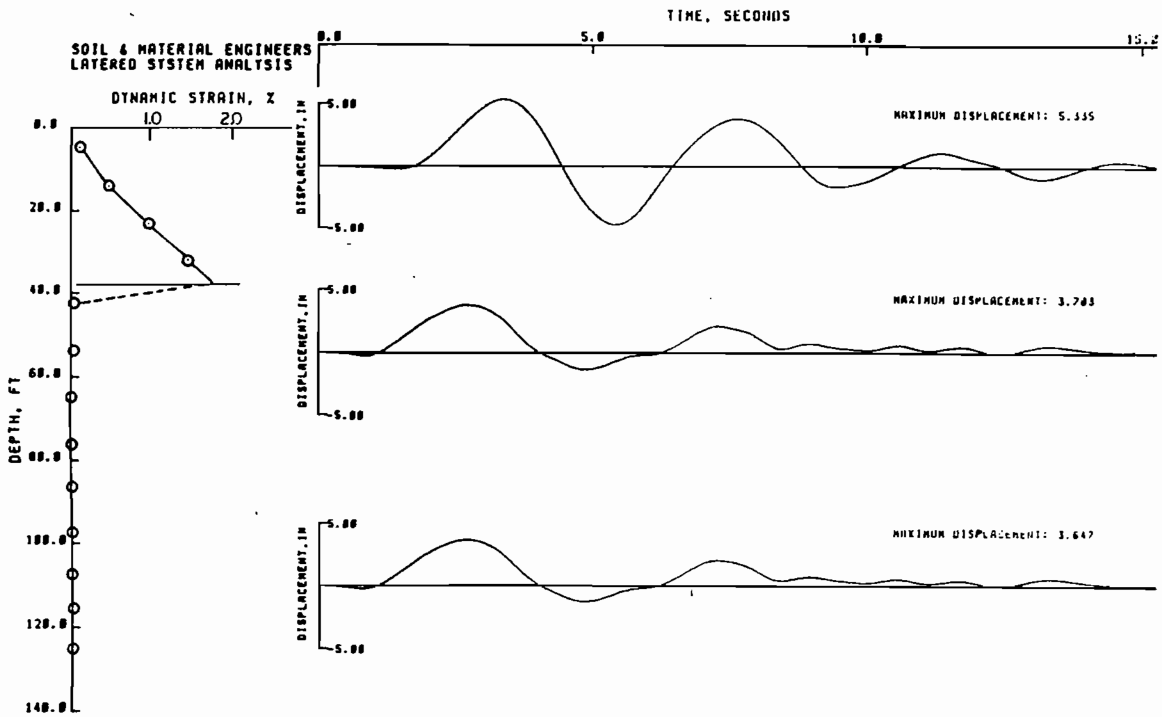

Figure 8 Free-Field Displacements - Spoil Island

Fortunately, the stability of a foundation relates not to the modulus of the subgrade, but to the undrained shear strength. It is important to note that the strength of the subgrade is not significantly influenced by cyclic loading. Therefore, cyclic loading will not affect the overall stability, but will increase deformations[7,8]. For cyclic strains less than 2 to 3%, the loss in undrained shear strength is less than 10% for typical marine clays[9,10] having plasticity limits of 40% and overconsolidation ratios of 3.5 to 6. These properties compare very closely with that of the Cooper Marl.

LATERAL CAPACITY-SINGLE PILE

The load-deflection response of a single vertical pile was predicted using two analytical methods. The first method is quasi-static technique for modeling cyclic lateral loading of piles[10]. This technique uses essentially static lateral pile analyses to predict the cyclic response of piles. An iterative solution technique is used that requires an initial assumption for cyclic strains and then subsequent adjustment of these values until the calculated and assumed cyclic strains are comparable. Currently this technique incorporates empirical marine clay properties based on prior tests[11] on San Francisco Bay mud samples. This soil has an estimated shear modulus of 500 ksf which compares very closely with that measured in the clayey soils beneath the Spoil Island.

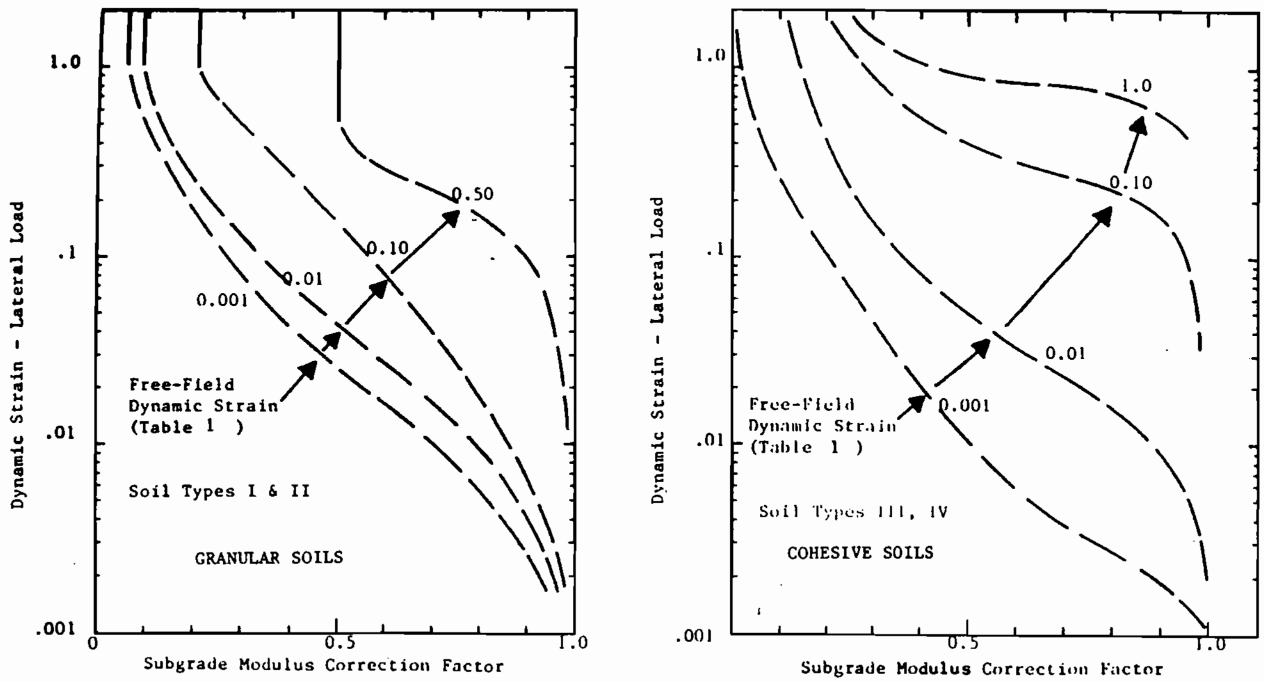

Figure 9 Modulus Correction Factor

A second analysis was performed using a finite difference one dimensional beam computer program[12,13] that provides for input of free-field seismic ground displacements and dynamic lateral loads concurrently. The free-field ground displacements used in that anlysis were similar to that obtained by double integration of the acceleration time histories obtained from the layered system analysis. This analysis method is significantly more complex than the quasi-static method.

Method one (quasi-static) performs the analysis of dynamically loaded lateral piles in the following procedure:

(1) Analyze the given pile for the maximum static + dynamic load and moment combination, and determine the distribution of displacements along the pile using dynamic subgrade coefficients obtained by multiplying the conventional static subgrade coefficient by the dynamic strain reduction factor and the cyclic reduction factor.

(2) Convert the displacements calculated in (1) into equivalent soil strains using the relationship[10]

Equivalent Soil Strain = Pc/6D x 100%
where Pc is the cyclic lateral displacement and D is the pile diameter.

(3) Using Figure 9, obtain the modulus correction factor for each profile due to the additional strains caused by the lateral load.

(4) If the correction factors are less than 0.9, then the analysis is complete. If the correction factors are greater than 0.9, then adjust the dynamic subgrade coefficients by multiplying the current values by the appropriate correction factor and repeat (1).

The use of conventional static modulus subgrade reaction values implies that the applied lateral lead is less than approximately 40% of the ultimate capacity of the pile. The ultimate pile capacity can be calculated using conventional static method or this criteria can be assumed to be satisfied if the level of maximum subgrade strain is less than approximately 2%.

A design example using the quasi-static method is presented on Table 2. This example uses a 140-foot cylinder pile within the profile found at the Spoil Island. Requiring two iterations, the final solution indicates a maximum displacement for the fixed head condition of 0.135 feet. Note that in calculating the modulus correction values from Figure 9, mean dynamic strains within a given layer are used. The solution results in a maximum subgrade strain of 0.4% and, therefore, can be assumed to be valid.

The design example was verified using the method two analysis. Profiles of pile displacements and moments obtained using both techniques are shown on Figure 10. Sinusoidal displacement time histories were used in method two because of the harmonic nature of the actual displacement time histories shown on Figure 8. This assumption greatly simplified the computer-related work. The two analytical methods give results with reasonable agreement. A quasi-static procedure such as method one will typically error on the conservative side because it neglects the phase relationship between seismic free-field motion and the structure response. The assumption that maximum free-field and structural induced strains occur at the same instant of time provides an upper bound solution.

SUMMARY

The quasi-static analysis presented herein for evaluation of the load-deflection response of a single vertical file during an earthquake is an attempt to deterministically analyze a probabilistic event. Current application of the method is limited by the paucity of data on the influence of cyclic stress history on the modulus of general categories of soils and the limited verification of the relationship used to related pile displacement and effective soil strain. The proposed analysis does offer significant simplicity and could easily be adapted using available free-field strain verse earthquake magnitude profiles to eliminate time domain from the procedure entirely. This technique is currently used extensively to evaluate liquefaction potential.[14]

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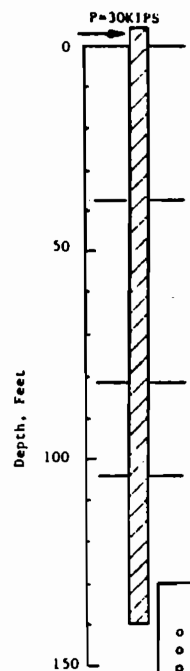

Soil Type	Coefficient Subgrade Reaction(1)	Cycle One: Modulus Subgrade Reaction(2)	Cycle One: Lateral Displacement (Feet)	Cycle One: Equivalent Cyclic Strain,%	Cycle One: Modulus Correction Figure 9	Cycle Two: Modulus Subgrade Reaction(3)	Cycle Two: Lateral Displacement (Feet)	Cycle Two: Equivalent Cyclic Strain	Cycle Two: Modulus Correction Figure 9
		0.018	0.107	0.32%		0.018	0.135	.135%	
III	0.10				1.0				1.0
		0.69 / 34.5	0.065	.196%		0.69 / 19.0	0.083	.083%	
I	5.0				0.55				.60
		74.5 / 6.4	.005	.015%		41.0 / 6.1	.0125	.038%	
IV	35.0				0.95				.98
		6.4 / 54.5	.0009	.0027%		6.1 / 54.5	.0009	.0003%	
II	300.0				1.0				1.0
		54.5	.00005	.0002%		54.5	.001	.003%	

Cylinder Pile
- o 66-inch diameter
- o I = 514,000 in4
- o E = 3,000 ksi

(1) Static Coefficient Subgrade Reaction x Free-Field Strain Reduction Factor
(2) Coefficient Subgrade Reaction x Pile Width x Depth Factor
(3) Static Coefficient Subgrade Reaction x Modulus Correction from Figure 9

Table 2 Method One Analysis - Spoil Island Profile

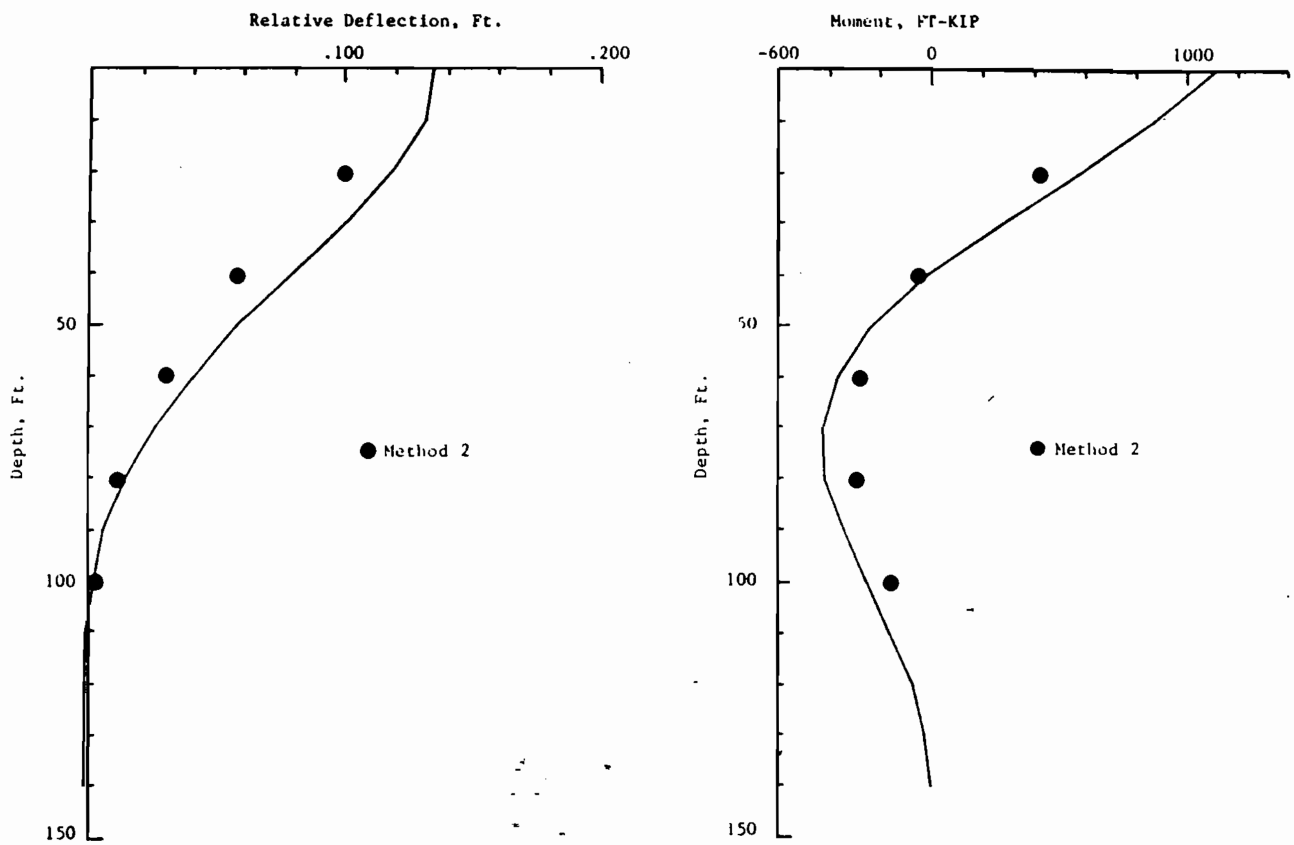

Figure 10 Method One Analysis - Spoil Island

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