LUMPED PARAMETER MODELING AND DYNAMIC RESPONSE EVALUATIONS OF SOIL-STRUCTURE SYSTEMS

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SUMMARY

The analytically predicted behavior of soil-structure systems subjected to dynamic loading is strongly influenced by behavioral assumptions incorporated in the modeling and the values assigned to parameters describing the system. Parameter sensitivity studies were conducted using software which performs dynamic soil-structure interaction analyses using an impedance model. A lumped parameter shear building modeled the superstructure; system springs utilized elastic and elastoplastic force-deformation relationships. Nonlinear soil-foundation interface behavior was also simulated. Two superstructure models, three soil behavior models, and two soil stiffnesses were studied in various combinations using simplified dynamic excitations. Results of the study were analyzed and appropriate conclusions noted.

THEORETICAL CONSIDERATIONS

The basic system analyzed in this study is shown in Figure 1. It consists of n superstructure masses and a foundation mass with translational springs and dashpots connecting the structural masses and the soil base and foundation. In addition, a rotational spring and dashpot are attached to the foundation. Shear building behavior is assumed and thus only translational deformations can occur in the superstructure.

Nonlinear system behaviors are normally experienced in strong motion earthquakes, and thus models that use purely elastic analyses can introduce significant errors. Nonlinear system behaviors were modeled in this study by using elastoplastic and bilinear elastoplastic springs. The lumped parameter modeling allowed the use of a simple system model so that the basic effects of the parameters of interest could be emphasized.

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SYSTEM MODELING

Soil-Foundation Modeling

Elastic, elastoplastic, bilinear elastoplastic, and classical fixed base models were used to represent different soil-foundation behaviors. Numerical values of the swaying and rocking spring constants for the elastic soil model were calculated using frequency independent elastic halfspace equations presented by Whitman and Richart (Ref. 1). Values of the spring constants are representative of soft and stiff soil settings. These same spring constants were used for the elastoplastic soil model. The maximum force that could be resisted by the swaying spring (i.e. the plastic plateau) was arbitrarily assumed to be 50 percent of the maximum spring force developed in the elastic analysis. Therefore, the elastoplastic translation spring represents either a slip condition at the soil-foundation interface, or nonlinear behavior of the foundation soil. The plastic plateau for the rocking spring was assumed to be 80 percent of the maximum force developed in the elastic analysis. The selection of the plastic plateau criteria allows a moderate amount of elastoplastic behavior rather than limiting the modeling to a simulation of a specific physical phenomenon.

The elastoplastic model rocking spring constants and plateaus was also used for the bilinear elastoplastic model. However, the swaying spring constants and plateaus for the side and bottom soils were selected so that their sums would be equal to the swaying spring constant of the elastoplastic model. Therefore, the initial soil characteristics for the bilinear elastoplastic and elastoplastic models were identical. However, the initiation of plastic behavior in the side-soil (modeled with a stop) or loss of foundation contact with the side soil causes different swaying stiffness characteristics for the bilinear elastoplastic model as compared to the elastoplastic model.

Structural Modeling

Two structures with different geometric and stiffness properties were used to evaluate effects of the various soil-foundation models. A tall flexible structure (10 stories) and a short stiff structure (1 story) were analyzed using each of the soil-foundation systems. Values of the geometry, stiffness, and mass parameters were selected to be somewhat representative of actual structures. The physical and vibrational characteristics of the two structures were marked different. The fundamental period of the tall structure was approximately ten times longer than that of the short structure. Elastic superstructure behavior of both structural models was assumed for all test cases.

Damping

Viscous damping was assumed and damping ratios for system components were held constant for all cases. Adjustment of damping values to account for plastic behavior of the springs in the response analysis was not attempted. Structural damping was 2 percent of critical while damping ratios for foundation swaying and rocking were taken to be 20 and 5 percent, respectively, and are representative of lightly damped systems.

Dynamic Load Characteristics

The dynamic load function was a harmonic ground acceleration as suggested by Veletsos et al (Ref. 2,3). The maximum amplitude of the ground acceleration was 0.2g (6.44 ft/sec^2). Excitation frequencies of 1.1 times the fundamental frequency of the respective fixed base structures were used to minimize biasing the response results.

TEST CASE RESULTS

Effects of Soil Stiffness on Natural Frequencies

Circular natural frequencies presented in Table 1 indicate that natural frequencies of the systems decrease as the soil stiffness decreases. As expected, the natural periods of the flexible based systems are longer than those of their respective fixed base structures. Natural frequencies of the tall flexible structure have less variation from the fixed base values than those of the short stiff structure. The dramatic modification in natural frequencies for the short stiff structure when soil-structure interaction is considered can have a very significant effect on the predicted response of such systems to dynamic loadings.

The tall structure excitation frequency of 5.6 radians/sec was between the first and second natural frequencies of the flexible based systems using either the soft or stiff soil setting. The ratio of frequency of excitation to system fundamental frequency (i.e. p/ω) was 1.16 for the soft soil system and 1.11 for the stiff soil system. However, for the short structure, the variation in natural frequency caused the excitation frequency of 57.7 radians/sec to be between the second and third natural frequencies for the soft soil system and approximately midway between the first and second natural frequencies for the stiff soil system. The respective p/ω ratios were 2.56 and 1.46. Therefore, test cases involving the tall structure were generally much closer to resonance than those with the short structure.

Effects of Soil Stiffness on System Responses

Peak response values for all test cases involving the short structure are given in Table 2. An increase in soil stiffness resulted in a decrease in the translations and rotations of the foundation for all soil models as would be expected in single degree of freedom and/or static behavior. However, unlike the foundation response, the maximum deformations in the structure were increased with increasing soil stiffness. Since the structure remained linear, the increases in deformation were accompanied by increases in force levels, as seen in the maximum values of base shear. This behavior is associated with inertial force resistance. Stiff soil springs abruptly decrease the motion of the foundation, which forces the structural spring to resist structural inertial forces. Softer soil springs provide a more gradual resistance to the entire system, thereby reducing the structural deformations and forces. The structural response was highest for the fixed base model.

Amplification factors (A.F.) for almost all peak response values for short structure cases were higher for stiff soil than for the corresponding systems supported on soft soils. The excitation frequency was close to the natural frequency for the fixed base system, and this case probably exhibited very large amplification factors due to the near resonance condition. Neither the soft or stiff soil system contained a natural frequency that approached the excitation frequency. However, the excitation frequency was closer to the fundamental frequency of the stiff soil system and this probably contributed to the somewhat larger amplification factors for the stiff soil settings.

Time history signatures for the short structure indicated a brief transient period followed by steady state vibration. For each soil model, the steady state base shear and top displacement were larger for the stiff soil than for the soft soil setting.

Peak response values for test cases involving the tall structure are summarized in Table 3. Again, an increase in soil stiffness resulted in a decrease of peak value foundation displacement and rotation for a particular soil behavior model. Peak values of the top displacement and base shear increased with increasing soil stiffness, as did the amplification factors for all response parameters. Increases in system responses appear to be attributable to the differences in energy dissipation capabilities and frequency ratios for the tall structure cases. Recall that the ratios of excitation frequency to fundamental system frequency were 1.16 and 1.11 for the tall structure on soft and stiff soil systems, respectively. Amplification factors for base shear and top displacement indicate that as the frequency ratio approaches one, the response of the structure increases. Also, the amplification factors approach those of the fixed base structure as the soil stiffness increases.

Tall structure time histories indicated a beating type vibration with the beating period of the soft soil system being shorter than that of the stiff soil system. This is consistent with SDOF behavior and with the maximum recorded values of base shear, i.e., systems with longer beating periods generally exhibited larger response amplitudes.

Effects of Soil Behavior Modeling on System Responses

For test cases involving the short structure, the foundation tended to displace (laterally) more for bilinear elastoplastic models than for those with elastoplastic behavior alone, and more for the elastoplastic models than the the elastic models. This behavior is consistent with the increased potential for plastic behavior for the elastoplasitc and bilinear elastoplastic foundation translation springs. An increase in foundation translation was associated with a reduction in rocking and this was most pronounced for the bilinear elastoplastic model. In fact, for the stiff soil system, the decrease in rocking for the bilinear elastoplastic model was sufficiently large to prevent plastic behavior of the foundation rotational spring.

The base shear and top displacement for the short structure were larger for systems with the elastic soil behavior model and smallest for those with the bilinear elastoplastic model. The structural response decreased with decreasing soil stiffness. The elastic soil model was stiffer than the elastoplastic model, which in turn was stiffer than the bilinear elastoplastic model. For small foundation displacements, translation spring constants are the same for all three models. However, for large foundation displacements, plastic behavior is initiated in the translation springs of the elastoplastic and bilinear elastoplastic models. This plastic behavior reduces the overall stiffness. Additionally, the steady state base shear was lower for the bilinear elastoplastic model than for the elastic and elastoplastic models. This results from the side soil being pushed away from the foundation and creating a softer system. The introduction of plastic behavior also smoothed the system response during the transient period of vibration.

For test cases involving the tall structure, foundation displacements and rotations were found to be greatest for systems with the bilinear elastoplastic model and smallest for the elastic behavior model. Conversely, the structural response (base shear and top displacement) was greatest for the elastic model and smallest for the bilinear elastoplastic model for a given soil stiffness. The introduction of plastic behavior modified and may have removed the beating effect present in the elastic soil models. This caused the bilinear elastoplastic model to reach steady state vibration more rapidly than the other two models. Thus, increasing plastic behavior appears to have a natural damping effect on the system response.

Foundation Wallowing Behavior

The test case with the tall structure on soft soil illustrates the mechanics of foundation "wallowing" behavior. The combined foundation lateral force-displacement curve for this test case is shown in Figure 2. The curve accounts for both the elastoplastic bottom soil spring and the elastoplastic side soil stops. The dotted line represents the assumed force-displacement relationship, while the continuous line tracks the response path of the system. Letters A through R correspond to particular points in time and are shown for convenience in tracking the time-history response of the system. The foundation first moves elastically to the right, then moves to the left and plastically compresses the side soil, then alternates motion to the left and right with plastic behavior being periodically exhibited in both the side and bottom soils. For example, the soil debonds from one side (say the left side) at point P and moves to the right while plastically deforming the bottom soil. At point Q it comes in contact with the right side soil and continues movement to the right while elastically deforming the side soil and plastically deforming the bottom soil. At point R it continues movement to the right while plastically deforming both the side and bottom soils. This behavior is graphically illustrated in Figure 3 which shows combined spring force and base displacement time history curves.

CONCLUSIONS

Soil-structure interaction can have a significant impact on the dynamic response of a system. Soil flexibility resulted in larger system natural periods than present in a corresponding fixed base system. These alterations of natural periods were more pronounced for short stiff structures than for tall flexible structures. Soft soil foundations increased natural periods above those corresponding to the same structure in a stiff soil setting. The vibrational characteristic alterations for short stiff structures were significant and created different time history responses for flexible based short structures relative to those for the same fixed base structure.

An increase in soil stiffness for a given soil behavior model reduced foundation displacements and increased the response of the superstructure. For a given soil stiffness, the response of the superstructure was greatest for an elastic soil behavior model and lowest for a representation permitting "wallowing" of the foundation. Also, the displacement of the foundation was found to increase with increasing potential for plastic behavior in the foundation translation springs. These system characteristics appear to be related to changes in the ratios of excitation frequency to system natural frequencies as well as to the increased spring softening and damping that plastic behavior implies.

ACKNOWLEDGMENTS

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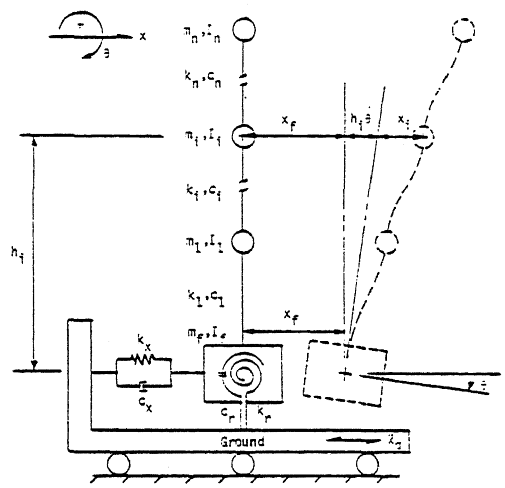

x_i = Horizontal displacement of structural mass with respect to undeformed position of superstructure

x_f = Horizontal displacement of foundation with respect to ground

θ = Rotation of foundation with respect to initial position

x_g = Horizontal ground displacement

Figure 1. General System and Its Degrees of Freedom.

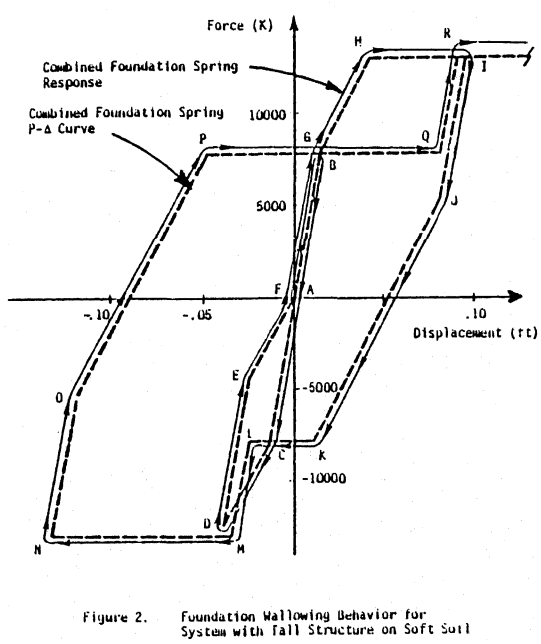

Figure 2. Foundation Wallowing Behavior for System with Tall Structure on Soft Soil

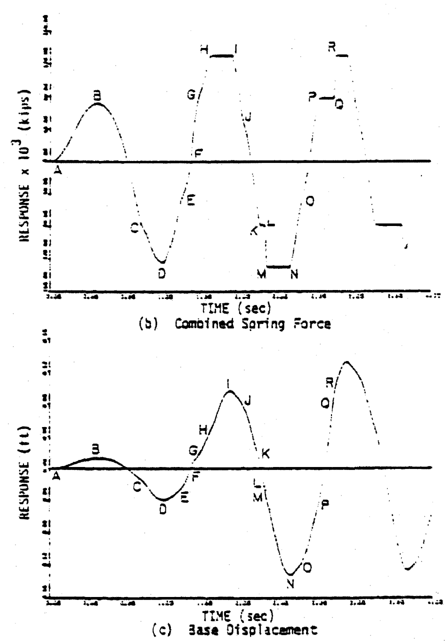

Figure 3. Foundation Wallowing Behavior for System with Tall Structure on Soft Soil

Table 1. Circular Natural Frequencies of Test Case Systems

Structure	Mode	Natural Frequency (radians/sec)		
		Soft Soil	Stiff Soil	Fixed Base
Tall	1	4.33	5.05	5.07
	2	13.13	13.41	13.47
	3	21.62	21.97	22.07
	4	28.94	29.34	29.45
	5	34.33	35.15	35.25
	6	42.15	42.76	42.90
	7	49.23	50.14	50.31
	8	50.79	55.65	55.99
	9	55.17	62.04	62.15
	10	61.33	70.37	71.08
	11	68.75	139.2	-
	12	73.53	313.3	-
Short	1	22.52	39.54	52.44
	2	48.58	83.64	-
	3	72.73	317.0	-

Table 2. Peak Response Values of Systems with Short Structure

Response Parameter	Fixed Base Model S1	Elastic Model		Elastoplastic Model		Wallowing Model	
		Soft Soil S2	Stiff Soil S3	Soft Soil S4	Stiff Soil S5	Soft Soil S6	Stiff Soil S7
Base Shear (kips)	18800	2200	6500	1750	5000	1700	4100
A.F.*	7.30	0.87	2.61	0.68	1.96	0.66	1.59
Top Displacement (ft)	.0168	0.0020	0.0060	.00160	0.0045	.00155	.00369
A.F.	7.30	0.87	2.61	0.68	1.96	0.66	1.59
Foundation Moment (ft-kips)	-	71600	84000	56000†	64000†	56000†	50000
A.F.	-	2.32	2.72	1.81	2.07	1.81	1.62
Foundation Rotation (10^{-6}rad)	-	31.4	0.91	27.2	0.68	25.5	0.54
A.F.	-	2.32	2.72	2.00	2.03	1.88	1.62
Foundation Displacement (ft)	-	0.0055	0.0027	0.0061	0.0030	0.0063	0.0032
A.F.	-	0.48	1.00	0.53	1.11	0.54	1.20

†Spring Plastic Plateau Value
*Amplification Factor = Maximum Dynamic Response/Modified Static Response

Table 3. Peak Response Values of Systems with Tall Structure

Response Parameter	Fixed Base Model T1	Elastic Model		Elastoplastic Model		Wallowing Model	
		Soft Soil T2	Stiff Soil T3	Soft Soil T4	Stiff Soil T5	Soft Soil T6	Stiff Soil T7
Base Shear (kips)	35000	24500	33000	19000	27000	18000	25000
A.F.*	5.45	3.82	5.14	2.96	4.21	2.80	3.89
Top Displacement (ft)	2.45	1.80	2.30	1.40	1.95	1.30	1.80
A.F.	7.58	5.57	7.12	4.33	6.04	4.02	5.57
Foundation Moment (10^{6}ft-kips)	-	2.20	3.00	1.76†	2.48†	1.72	2.25
A.F.	-	5.29	6.98	4.08	5.75	3.99	5.22
Foundation Rotation (10^{-4}rad)	-	10.1	0.326	10.2	0.264	7.54	0.244
A.F.	-	5.29	6.98	5.39	5.65	3.99	5.22
Foundation Displacement (ft)	-	0.044	0.014	0.093	0.066	0.132	0.095
A.F.	-	3.38	4.67	7.15	22.0	10.1	31.7

†Spring Plastic Plateau Value
*Amplification Factor = Maximum Dynamic Response/Modified Static Response