

Modeling the Effects of Soil-Structure Interaction on a Tall Building Bearing on a Mat Foundation

Examining soil-structure interaction can result in more efficient structural designs.

LEWIS EDGERS, MASOUD SANAYEI &
JOSEPH L. ALONGE

The interaction of a building, its foundation and the underlying soils may have important effects on the behavior of each of these components as well as on the overall system behavior. For example, the relative stiffness of a building structure, its mat foundation and the soils that support the foundation will influence the stresses and displacements of both the structure and soil. Soil-structure interaction (SSI) effects are sometimes neglected by the use of a structural model supported on a fixed base. Other

simple models assume an ideally flexible or infinitely rigid foundation on an elastic subsoil.

An investigation of the effects of SSI on the stresses and displacements in the structure and the soil of a model fifty-story steel frame structure with a concrete mat foundation bearing on a deformable soil was undertaken as a means of best understanding how to perform and apply SSI analyses. The study included investigating the effects of the stiffnesses of the building, its mat foundation and an elastic subsoil on the stresses, internal forces and displacements of the building, foundation and subsoils. The soil-structure model also considered the effects of foundation embedment.

Development of Computer Models

The study of SSI was conducted with a building frame model developed within the context of research on the effects of increased wind

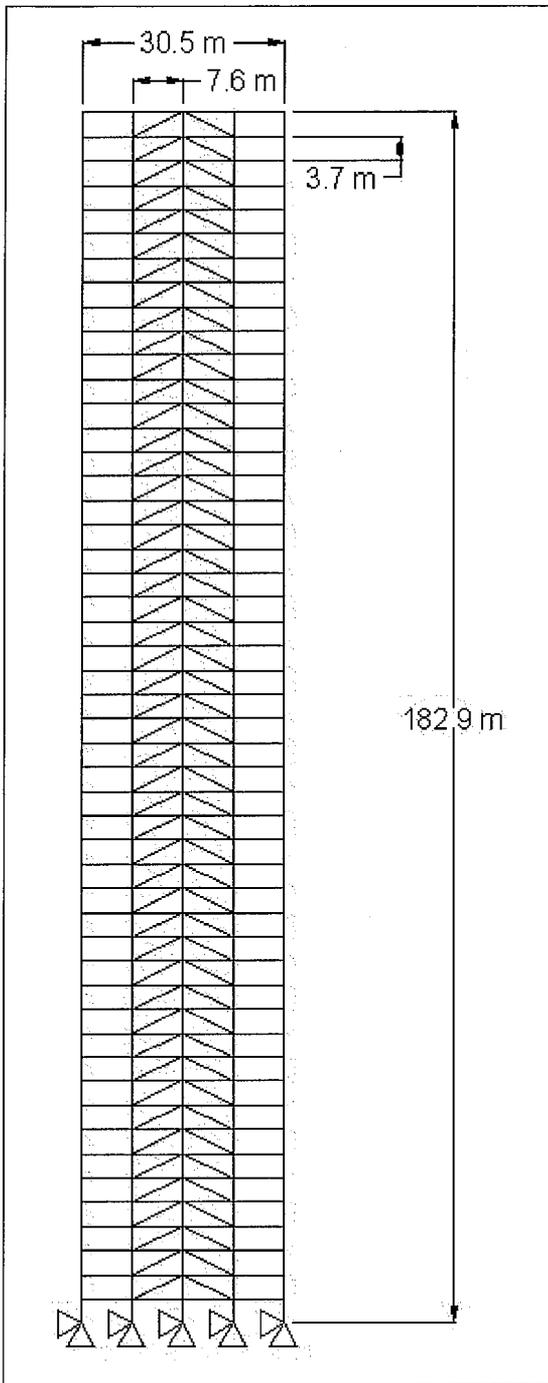


FIGURE 1. ANSYS model of the fifty-story building pin-supported on a rigid base.

loads due to global climate change on tall buildings in Boston.¹ The building model is representative of many taller buildings found in large cities.

For the initial analyses, an ANSYS model of the building frame was pin-connected to a rigid base (see Figure 1). The two-dimensional building model — 182.9 meters (600 feet) high by 30.5 meters (100 feet) wide by 0.3 meters (1 foot) — consists of 255 nodes and 550 elements. The framing system is based on a steel member with core bracing similar to that of a Pratt brace. The floor height is 3.66 meters (12 feet) and is typical of many tall buildings.² It uses the Beam3 as frame elements and Link1 as truss elements. The framing material is assumed to be steel and the flooring system is assumed to be metal decking with a concrete slab 10.2 centimeters (4 inches) thick. The wind loads were applied as point loads along the left side of the structure, and the vertical dead and live loads were applied together as uniform loads to the horizontal members. Gravity loads actuate the self-weight of the structure. The connection between the building and mat foundation was modeled by a pin connection at the base of the columns. Figure 2 shows a close-up of the building frame, lateral load carrying system and the pin connections to a rigid support. The structure is fixed at the base in order to examine its response (since the structure is ordinarily analyzed by ignoring the SSI).

Figure 3 shows the finite-element model of the building frame supported by a mat foundation bearing on a stiff linear elastic soil. This model was developed in order to simulate realistic foundation design conditions. The soil mass was represented by a mesh 213 meters (700 feet) wide by 152 meters (500 feet) deep, consisting of forty-two quadrilateral plane strain elements. A set of elements and nodes are added to the top of the soil mass to represent the concrete mat. The coincident nodes at the soil-concrete interface were merged so that there is full continuity with no slippage at this interface along the base of the foundation.

A two-dimensional, rather than three-dimensional, structural model was developed in order to increase computational efficiency. In order to represent a three-dimensional structure in two dimensions, the element stiffness and loadings were distributed over a unit two-dimensional slice of frame bents spaced

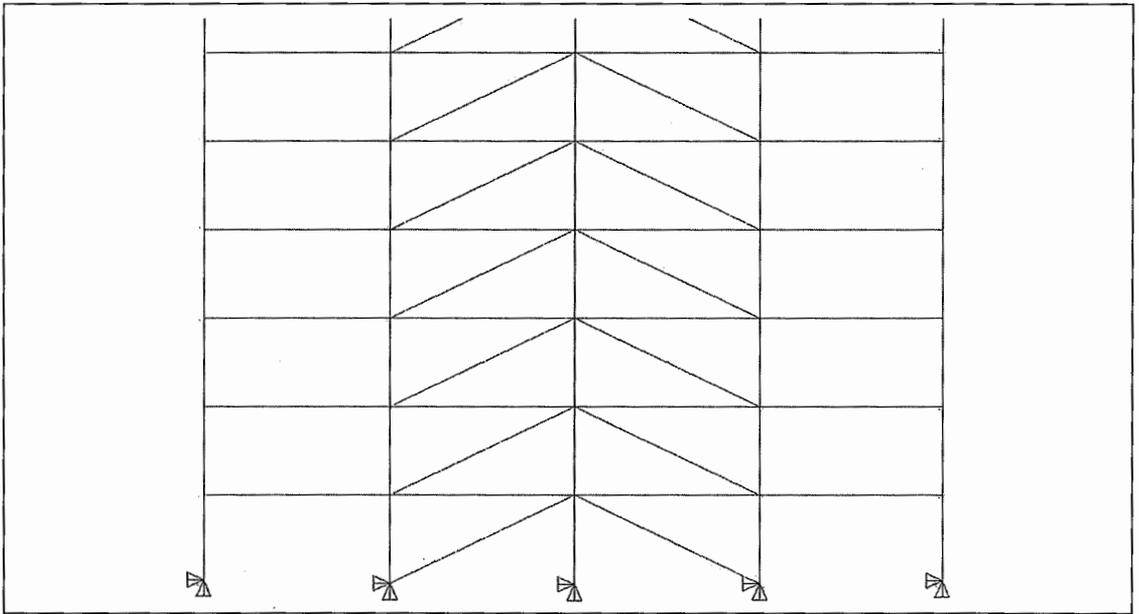


FIGURE 2. The lower floors of a fifty-story building pin-supported on a rigid base.

at 7.6 meters (25 feet). The bending rigidity, EI , and the axial rigidity, EA , of the building's beams and columns, located at the 7.6-meter (25-foot) bay spacing, were scaled by reducing the common elastic modulus parameter, E , by one-twenty-fifth. Thus, it was unnecessary to adjust the moment of inertia, I , or cross-sectional area, A , of each member. The material density for the discrete members was scaled by one-twenty-fifth so that full self-weight was evenly applied over each bay. No scaling was applied to the properties of the concrete mat foundation and the subsoil because they were continuous. Table 1 summarizes the material properties used for these analyses. A two-dimensional model would not be applicable for situations without symmetry in the third dimension. For these situations, full three-dimensional analyses can be performed with finite-element packages (such as ANSYS and PLAXIS 3D Foundation).

The dead, live and wind loads used in this analysis are based on the Massachusetts State Building Code.³ Seismic loads are not considered. Dead load includes the weight of the framing, flooring, ceiling and mechanical, and partition load (assumed to be office space). The live load was assumed to be an average of the typical loads found in offices, office lob-

bies and corridors. The wind loads are based on Zone 3 for the Boston metropolitan area, and exposure B for towns and cities. All applied dead and live loads were transformed to represent the forces acting on a unit slice of the building model. To do so requires a one-twenty-fifth scaling of the weight of all steel elements spaced at 7.6 meters (25 feet) but no adjustment of distributed loads. The wind loads were concentrated at each of the building's floor levels. Tables 2 and 3 summarize the loads applied to the unit slice model.

Figure 4 shows the details of the finite-element model, modified to describe an embedded foundation. The computer model of the excavated areas includes both soil elements and elements representing foundation walls, mat foundation and two stories of an underground garage structure. The linear elastic model requires full continuity between the soil and the concrete walls and mat. The embedded model also includes two levels of columns and concrete beams to represent the underground part of the structure. The entire mesh includes 7,083 nodes and 6,948 elements. For the purpose of these linear-elastic analyses, excavation support issues have been neglected.

The ANSYS analyses for staged excavation and construction were performed as follows:

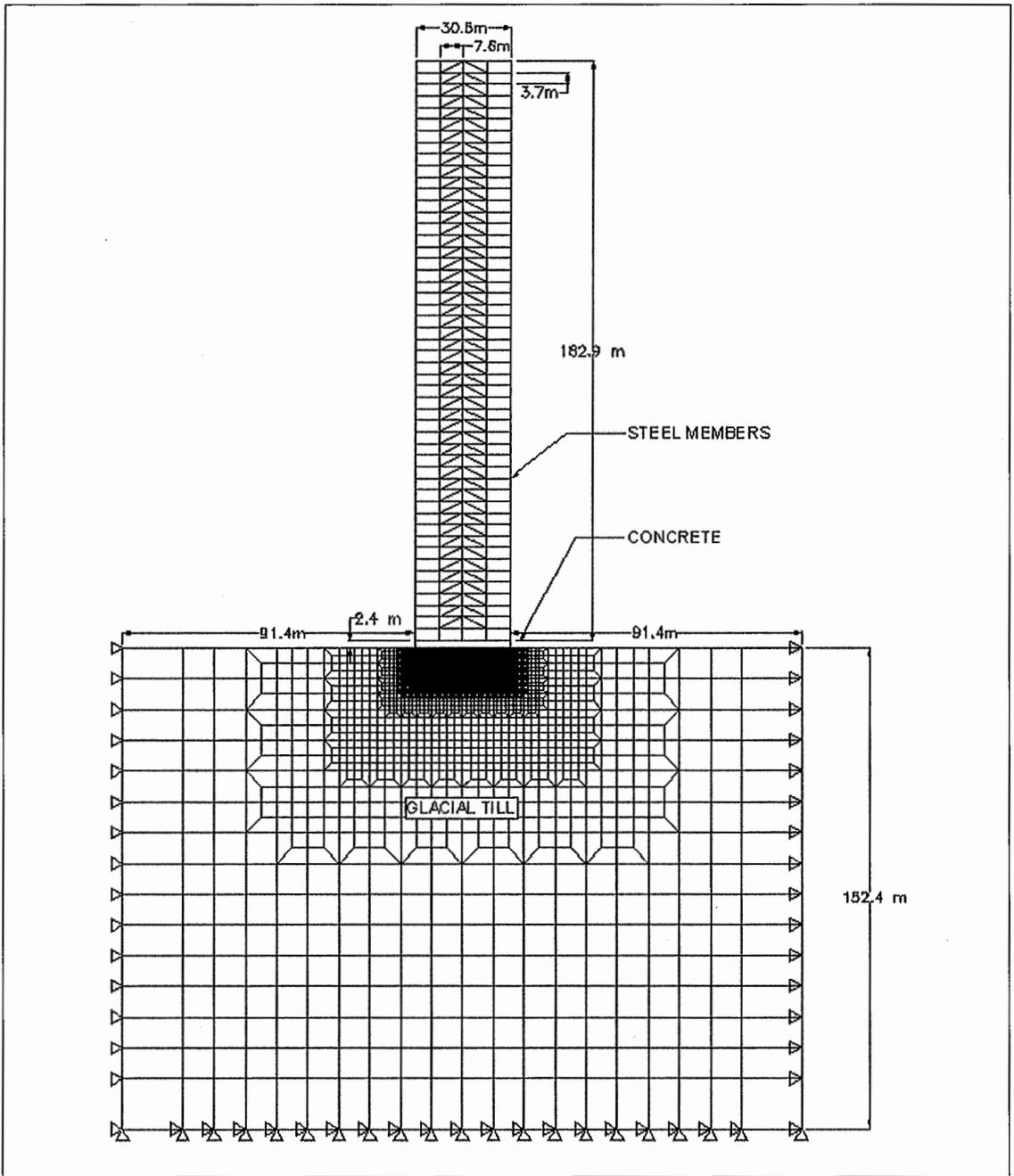


FIGURE 3. An ANSYS model of a fifty-story building supported on a mat foundation and soil.

Initial Step. Generate initial stresses in the soil (mat and building elements deactivated [see Figure 3]).

Step 1. Change material properties for the right foundation wall (soil to concrete [see Figure 4]).

Step 2. Change material properties for the left foundation wall (soil to concrete [see Figure 4]).

Step 3. Deactivate elements representing the excavated soil from between the walls (see Figure 4).

TABLE 1.
Material Properties

Material	Property	Full Value	Scaled by 1/25
Steel	γ	77 kN/m ³ (490 pcf)	3.1 kN/m ³ (19.6 pcf)
	ν	0.30	—
	E	199,946,880 kPa (4,176,000 ksf)	7,997,875 kPa (167,040 ksf)
Soil	γ	20.4 kN/m ³ (130 pcf)	—
	ν	0.25	—
	E	957,600 kPa (10,000 ksf)	—
	K_o	0.40	—
Concrete Foundation	γ	23.6 kN/m ³ (150 pcf)	—
	ν	0.15	—
	E	27,770,400 kPa (580,000 ksf)	—

Step 4. Activate mat elements and change material to concrete (see Figure 4).

Step 5. Activate the fifty-story frame (see Figure 3); apply dead and live loads (see Table 2).

Step 6. Apply wind (see Table 3) loads to the fifty-story frame.

(The sign conventions for the results presented here are that downward displacements [settlements] and compressive stresses are negative.)

Linear Elastic Analyses

Verification Analyses. An initial series of ANSYS runs were performed using the soil mesh of Figure 3, without the building frame, in order to verify the operation of the program, including mesh generation and the calculation of initial geostatic stresses.⁴ Loading conditions included uniform one-dimensional vertical loading across the entire top boundary as well as uniform vertical loading applied to

TABLE 2.
Summary of Dead & Live Loads (N/.3m) Applied to the Unit Slice Model

Dead Loads, N/.3m (plf)		Live Loads, N/.3m (plf)	
Floor	220 (50)	Offices	222 (50)
Ceiling/Mechanical	44.5 (10)	Lobbies	444 (100)
Partition	89 (20)	Corridors	356 (80)
Steel	71 (16)	Average	342.5 (77)
Total Applied	427 (96)	Total Applied	342.5 (77)
Total Dead & Live Load Applied = 427 + 342.5 = 770 N/.3m (173 plf)			

TABLE 3.
Summary of Wind Loads Applied
to the Unit Slice Model

Floor	Load, N (lb)
1-8	1121 × 8 (252 × 8)
9-12	1388 × 4 (312 × 4)
13-16	1601 × 4 (360 × 4)
17-20	1815 × 4 (408 × 4)
21-25	1975 × 5 (444 × 5)
26-33	2189 × 8 (492 × 8)
34-41	2455 × 8 (552 × 8)
42-49	2722 × 8 (612 × 8)
50 (Roof Receives Half)	1361 × 8 (306 × 8)
Total	98,350 (22,110)

the 30.5-meter (100-foot) central foundation mat area. The computed stresses for these simple loadings agreed with the results given by classical elastic theory.⁵ The magnitudes of the ANSYS computed settlements were checked using simple elastic theory, including the effects of a rigid layer at finite depth⁶ and foundation embedment.⁷ Note that ANSYS does not automatically correct for the settlements due to the soil's self weight; therefore, these settlements must be subtracted from the total settlements caused by any additional loads. The ANSYS computations were also checked by comparison with the stresses and displacements computed by PLAXIS, assuming linear elastic soil behavior. Alonge describes these verification analyses in detail.⁴

Parallel ANSYS and PLAXIS analyses were performed for the building-mat-soil model in connection with parametric studies for SSI

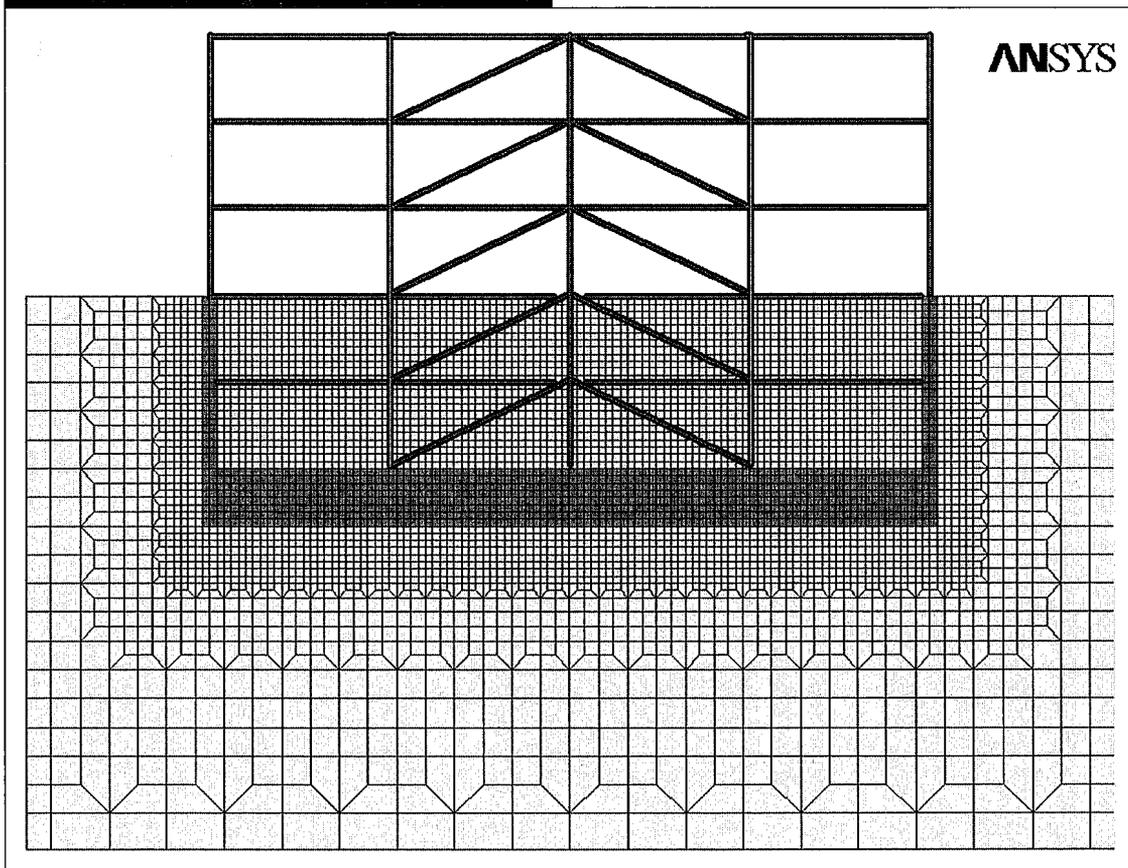


FIGURE 4. Embedded building substructure and foundation.

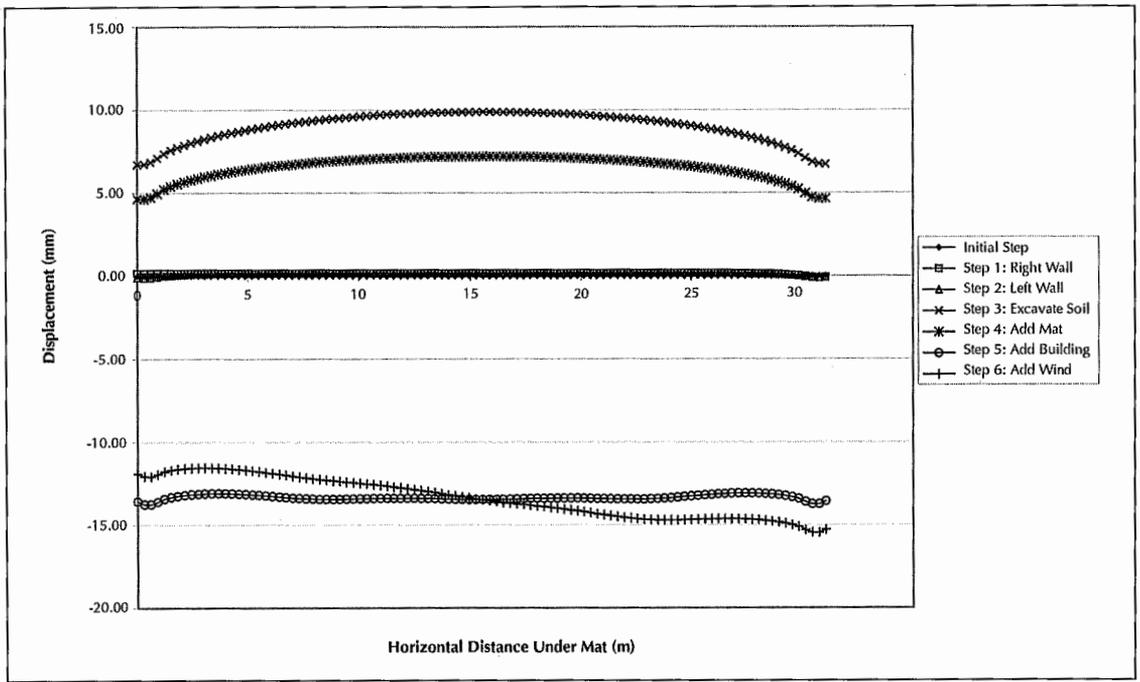


FIGURE 5. Stages of vertical mat foundation displacements.

(described later). Because PLAXIS cannot model the structure in detail, the column loads were first computed by ANSYS using the building-foundation-soil model. These column loads were then applied as an input to PLAXIS with a linear elastic soil model. The programs computed virtually identical stresses and displacements in the soil and concrete mat, which verified that the building reactions at the mat from the ANSYS model could be used in the PLAXIS model to find the stresses and deformations. This application is permitted due to the fact that the column reactions from ANSYS capture the load and stress redistributions in the combined building-mat-soil model.

Vertical Displacements (Settlements). Figure 5 shows the settlements computed by ANSYS for each step of the embedded model analysis, which had been adjusted for the settlements due to the initial self-weight of the soil. The first and second steps show little movement as the foundation walls are put into place. Step 3 shows a positive upward displacement due to the large mass of soil excavated from between the foundation walls. Step 4 shows some downward displacement due to the addition of the concrete mat. The net displacement is

still up at this point because the concrete weighs less than the soil removed. Step 5 shows a net downward displacement because the weight of the building and loads are heavier than the soil. Step 6 shows the skew due to the addition of the wind loads. Note, however, that the details of excavation performance and support have been neglected for these elastic analyses.

Figure 6 shows the effects of foundation embedment on the final computed settlements. The surface model shows the same pattern of foundation settlements but with magnitudes that are almost twice as large as the settlements of the embedded foundation. The embedded foundation settles less because of the net load reduction due to the weight of excavated soil, the smaller thickness of soil beneath the foundation and the beneficial effects of confinement (e.g., see Reference 7). Note that the building frame model of Figure 1 experiences no settlements since it is pinned to a rigid base.

Stresses in the Foundation Mat. The thickness of the concrete mat, usually determined by punching shear around columns,⁸ may affect the contact stresses, foundation settlements,

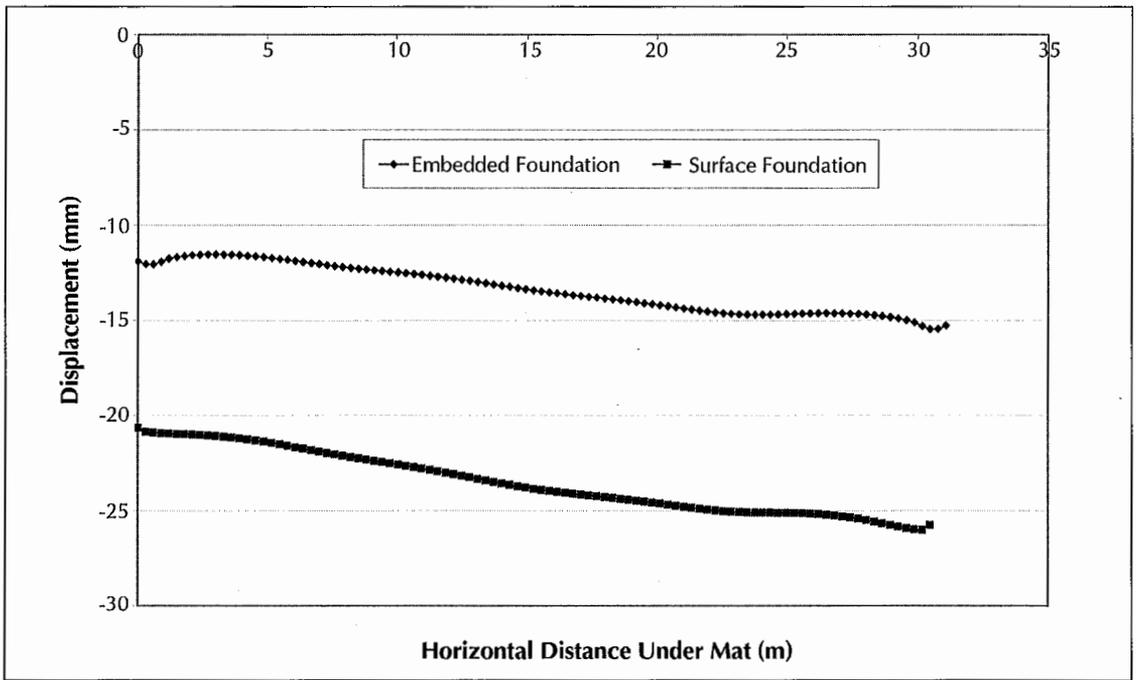


FIGURE 6. The effects of foundation embedment on computed settlements.

building deflections, and mat and building bending moments. The baseline computations were performed for a 2.44-meter (8-foot) thick concrete mat. ANSYS computations also performed for a 1.83-meter (6-foot) thick mat show similar general variations of vertical and horizontal contact stresses and settlements of the embedded foundation for the two mat thicknesses. However, the 2.44-meter (8-foot) thick mat produces slightly more uniform vertical contact stresses, as illustrated by Figure 7. The computed settlements and lateral deflection of the building centerline are almost identical for the two mat thicknesses.⁴ Note also that contact horizontal shear stresses were greatly reduced for the embedded foundation because of load transfer into the building's foundation walls bearing on the foundation mat below grade. Alonge presents and discusses all of these results in detail.⁴

The bending stresses in the concrete mat are important because they are a measure of the mat bending moments. Figures 8 and 9 show the bending stresses at the nodes 0.3 meters (1 foot) below the mat top surface (see Figure 8) and the nodes 0.3 meters (1 foot) above the mat bottom surface (see Figure 9). The left-to-

right wind loading causes an asymmetrical horizontal stress distribution. Building columns are located at 0, 7.7, 15.2, 22.9 and 30.5 meters (0, 25, 50, 75, and 100 feet). Significant stress concentrations were computed at column locations, compressive near the top of the mat (see Figure 8) and tensile near the bottom of the mat (see Figure 9). Between columns, the 1.83-meter (6-foot) thick mat shows smaller compressive stresses (see Figure 8) and larger tensile stresses (see Figure 9) than the 2.44-meter (8-foot) thick mat. This condition would require the use of more reinforcing bars in the 1.83-meter (6-foot) reinforced concrete mat.

Bending Moments in the Building Frame. Figure 10 shows the lower floors of the fifty-story frame for which the bending moments were computed by ANSYS for both the 1.83-meter (6-foot) and 2.44-meter (8-foot) thick mats (see Figure 11). Figure 11 shows the bending moments in the fifty-story frame due to its self-weight, dead, live load and wind loads. The bending moments are non-symmetrical due to wind loading. In general, bending moments in the beams and columns are not very different for either mat, indicating that both provide suf-

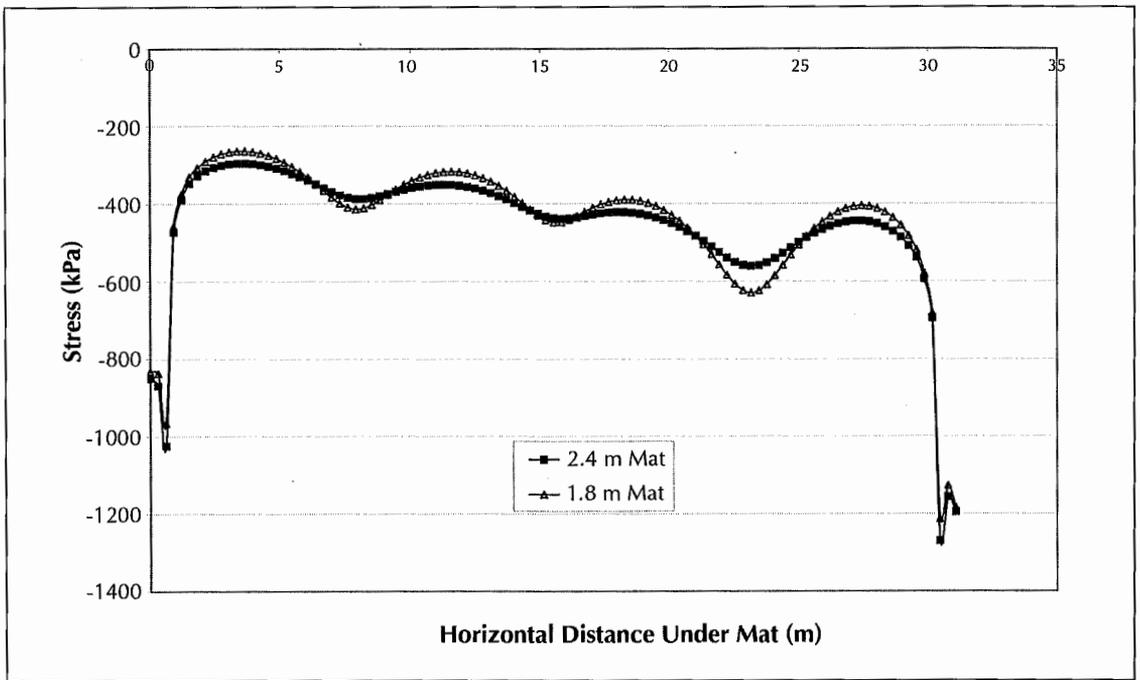


FIGURE 7. The effect of mat thickness on vertical contact stresses.

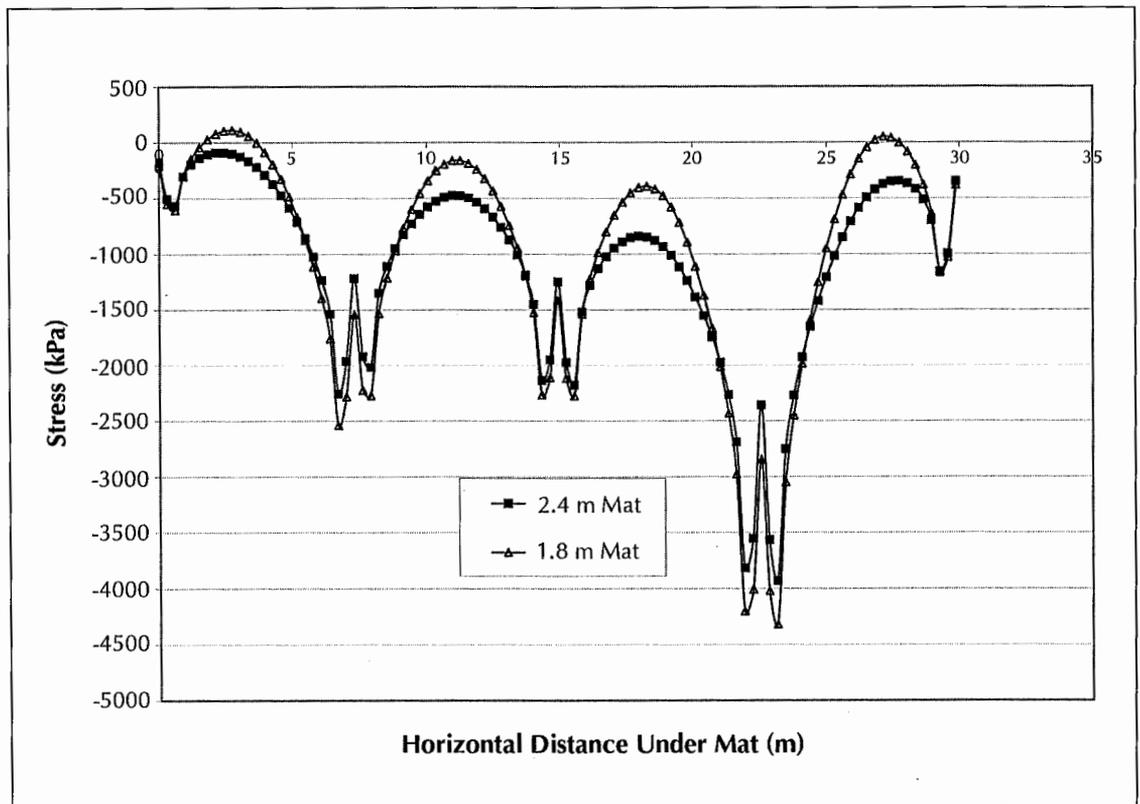


FIGURE 8. Bending stresses 0.3 meters (1 foot) below the top of the mat foundation.

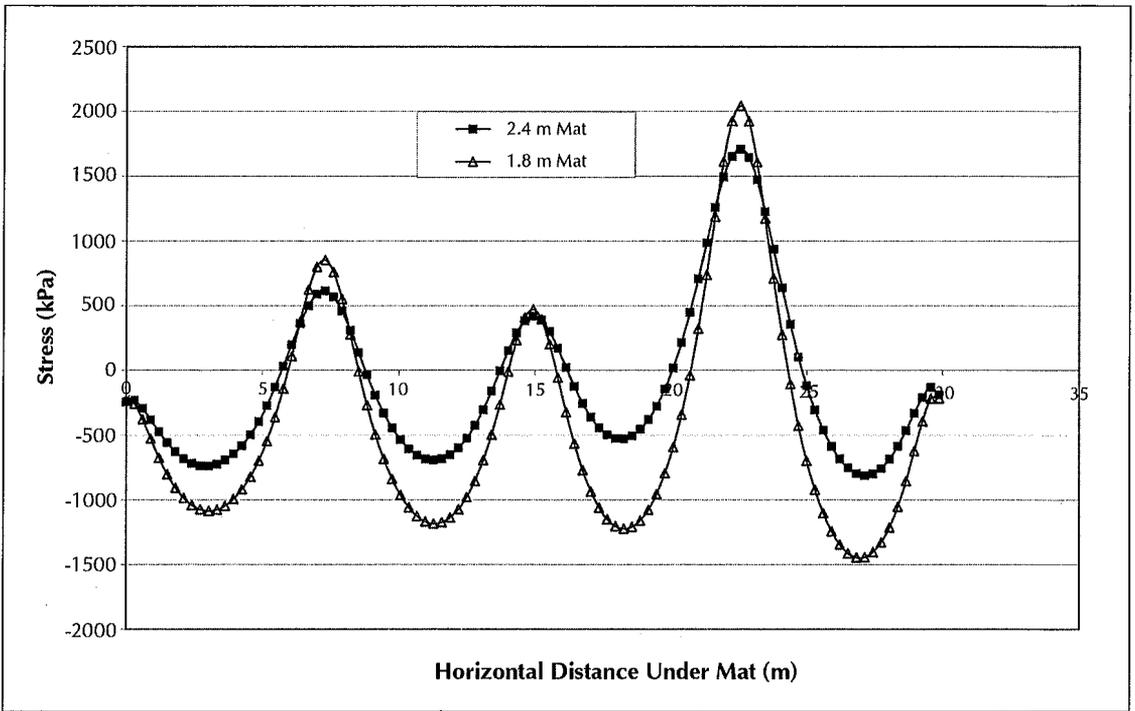


FIGURE 9. Bending stresses 0.3 meters (1 foot) above the bottom of the mat foundation.

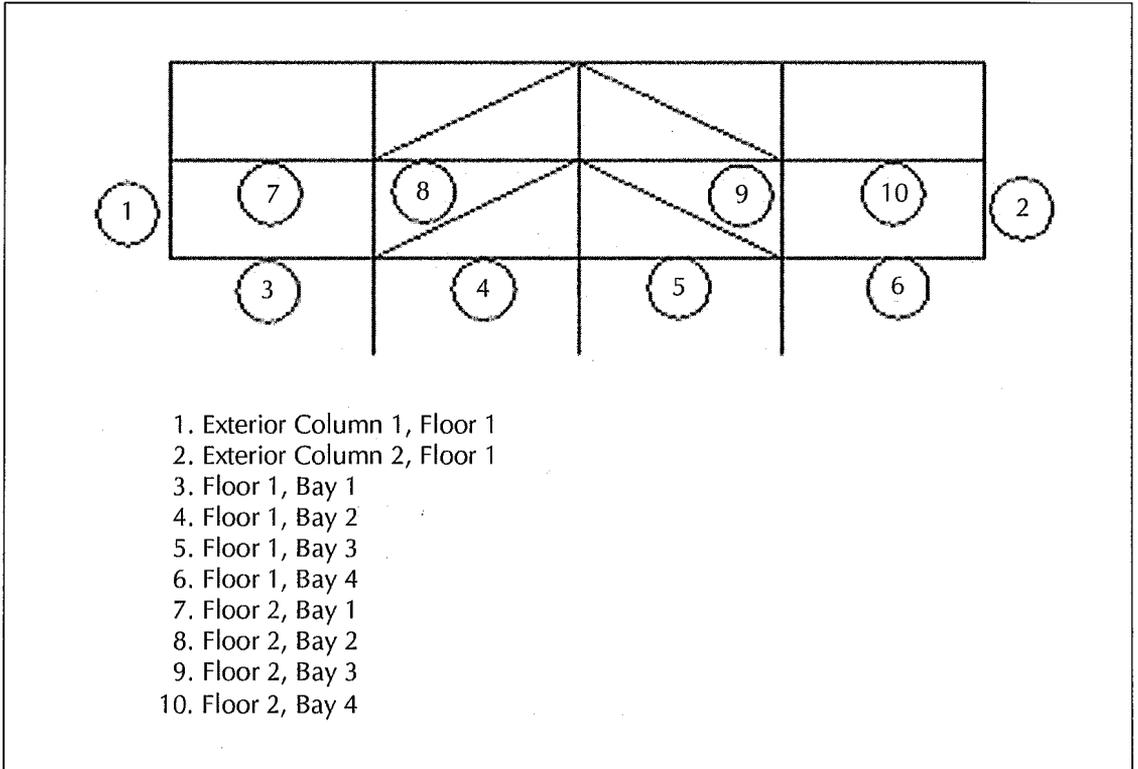


FIGURE 10. The location of structural members for bending moment comparison.

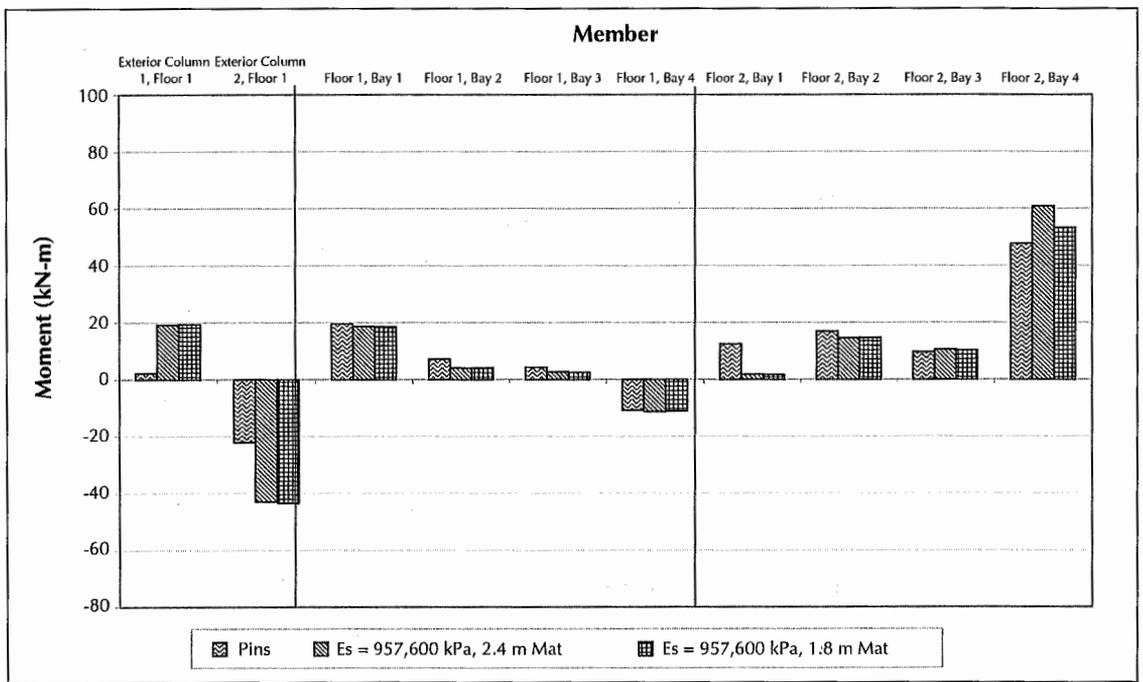


FIGURE 11. The effect of mat thickness on structural element bending moments.

ficient rigidity to uniformly and effectively support the structure. These two mat thicknesses satisfy the American Concrete Institute (ACI) punching shear requirements.

Figure 11 also shows the results of an analysis in which the structure was pinned to a rigid foundation, with no deformable soil. These results show variation in the bending moments at the leeward exterior column by a factor of 2. These results suggest the importance of modeling the foundation and subsoils with the structure in order to estimate SSI effects and the bending moments in the exterior columns and beams. However, note that the variation should be considered within the context of the overall column design using the interaction of axial loads with bending moments. Also, there are often other redundancies and load redistribution mechanisms in structural systems of tall buildings that facilitate the transfer of additional loads induced by mat relative deformations. Perhaps more significantly, the model did not directly account for construction staging and the application of loads with time. Effects predicted by the SSI analysis would likely be applied gradually as the structure was

sequentially built. Therefore, the structure would have the ability to shift and transfer forces and moments more gradually. Even with these mitigating factors, however, the SSI model can lead to significant changes in structural member forces and moments.

Effects of Soil Modulus. The baseline studies have been performed with an effective stress Young's soil modulus, E , of 957,600 kPa (20,000 ksf) and a 2.33-meter (8-foot) thick mat. In order to investigate the effects of variations of the modulus typical of stiff soils likely to be used for the foundation support of tall buildings, the soil modulus was reduced to 239,400 kPa (5,000 ksf) and 478,800 kPa (10,000 ksf). Figure 12 shows that, with a reduction in soil modulus, the vertical stress distribution immediately below the foundation mat (0.3 meters [1 foot]) becomes more uniform, with less pronounced stress concentrations beneath the columns. Overall, the variations in soil vertical stress were insignificant. The horizontal stresses and shear contact stresses were similarly affected.⁴

The vertical displacements increase proportionally as the soil modulus is decreased (see Figure 13). Figure 14 shows the increase in

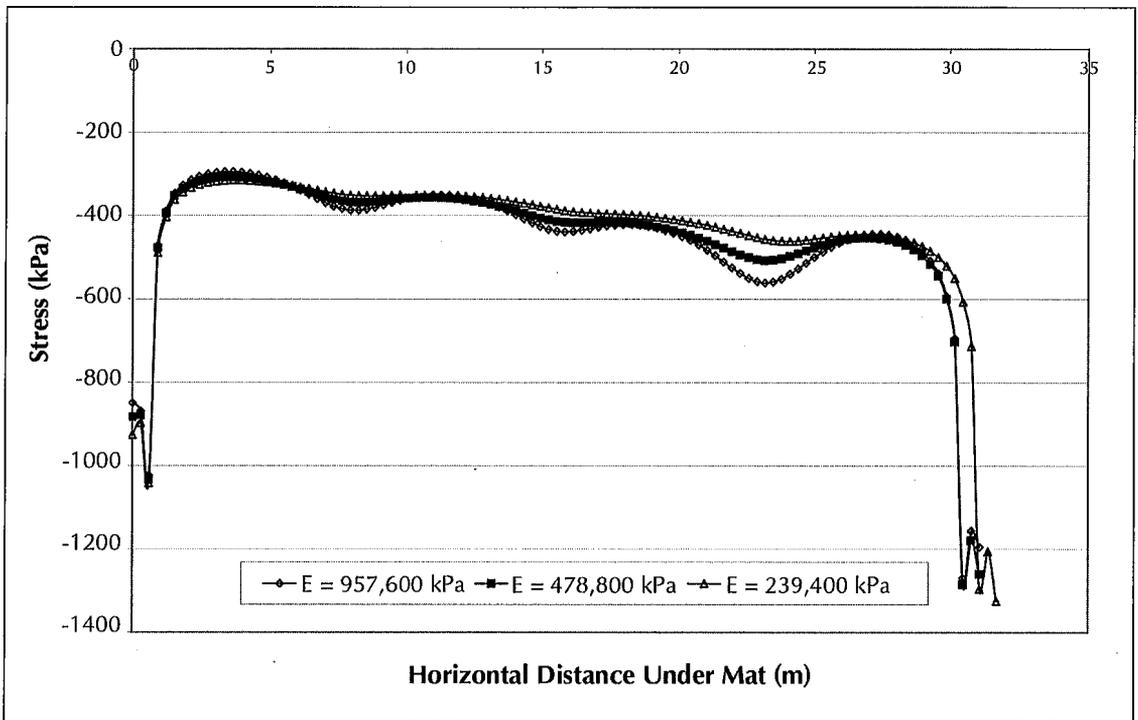


FIGURE 12. The effect of soil modulus on mat vertical stresses.

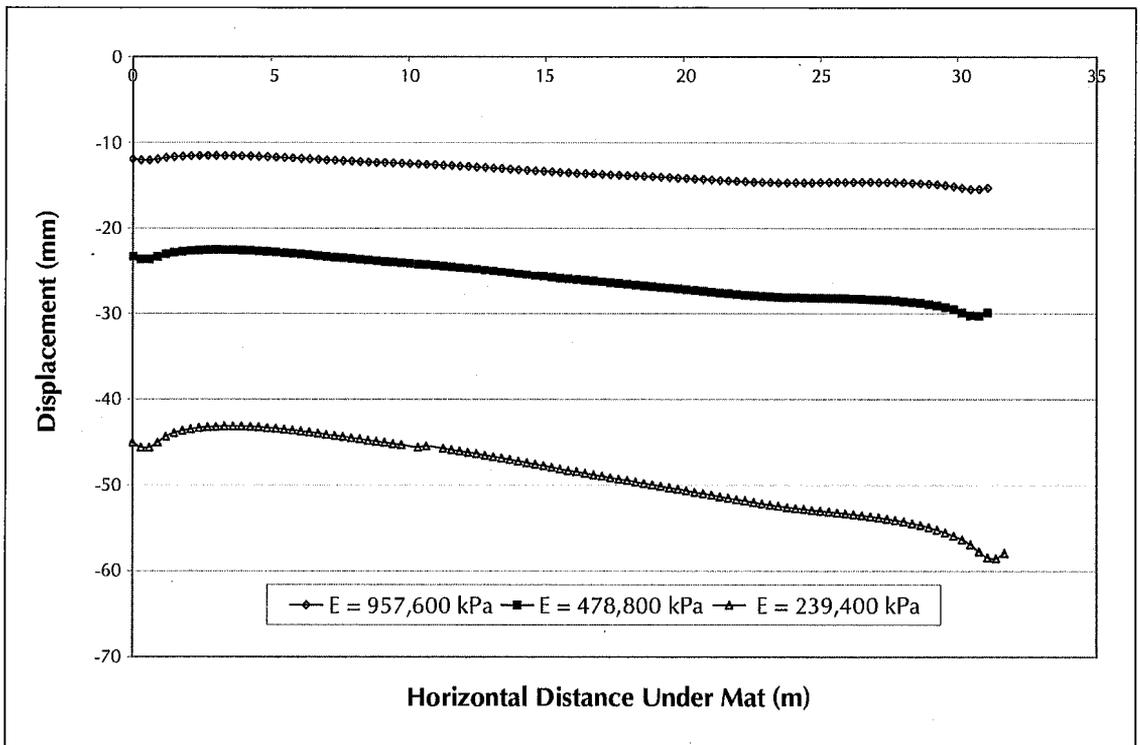


FIGURE 13. The effect of soil modulus on mat vertical displacements.

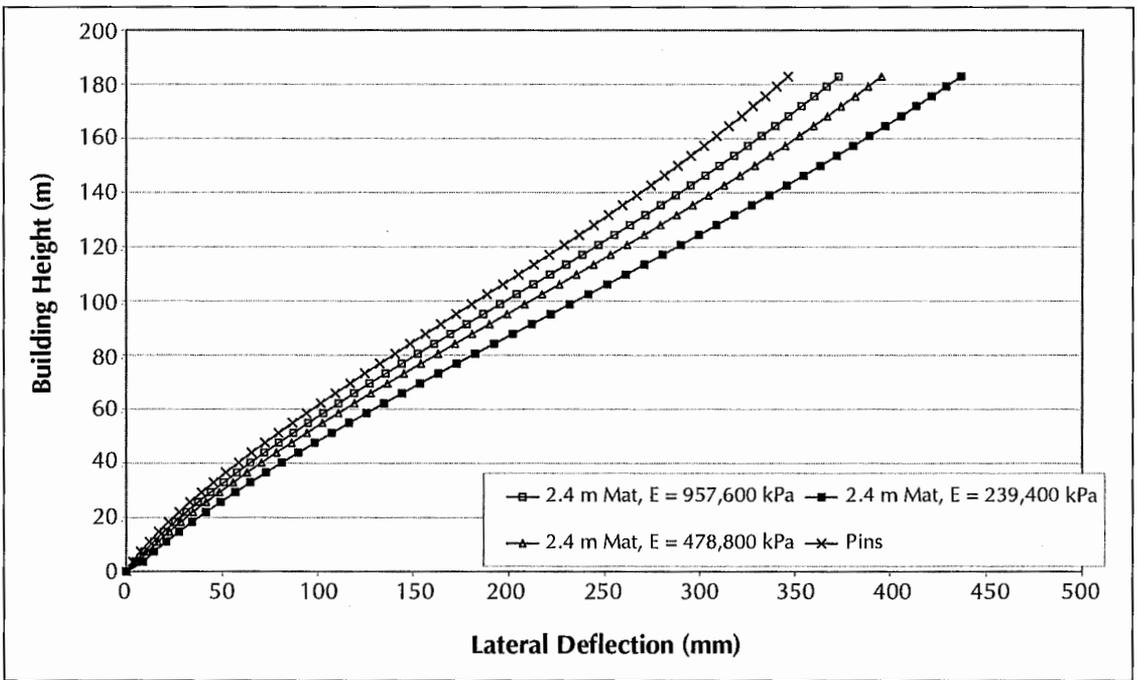


FIGURE 14. The effect of soil modulus on the lateral deflection of the building centerline.

centerline deflection with the decrease in soil modulus from 957,600 kPa (20,000 ksf) to 239,400 kPa (5,000 ksf). This figure also shows the results of an analysis in which the structure was pinned to a rigid base with no deformable soil. The resulting lateral deflection, due entirely to the deformability of the structure, underestimates the total lateral deflection that includes the SSI effects of the mat foundation and deformable soil.

Figures 15 and 16 show the bending stress distributions computed in the concrete mat at the nodes 0.3 meters (1 foot) below the mat top surface and the nodes 0.3 meters (1 foot) above the mat bottom surface, respectively. The compressive (negative) and tensile (positive) stress concentrations appearing at the top and bottom of the mat that were noted earlier (see Figures 9 and 10) are still evident. However, the concentrations become much larger with decreasing soil modulus, more than doubling for the range of soil moduli assumed. Figures 15 and 16 resemble mat bending moment diagrams superimposed with stress concentrations due to column loads.

Figure 17 shows the computed bending moments at representative members selected

from the fifty-story frame shown in Figure 10, for the variations of soil modulus considered, as well as for the building frame pinned to a rigid base. It shows the bending moments in the fifty-story frame due to its self-weight, dead and live load, with wind loads. The structural behavior is asymmetrical about the centerline of the frame due to wind load. Bending moments in the exterior leeward columns (right in Figure 10) increase significantly as the foundation system softens from pins on a rigid base to soil with decreasing stiffness. Figure 17 also shows that when the wind load is applied, the bending moments in leeward exterior beams on the second floor increase considerably with decreasing foundation stiffness (shown to the right in Figure 10). When the foundation and subsoil rigidity are not modeled (pinned condition), bending moments at the exterior columns and beams can be underestimated by factors of 2 to 3. Incorrect estimates of soil modulus can lead to large errors in the bending moments computed at critical locations. Again, this increase should be considered within the context of interaction of the axial loads and bending moments, the role of other redundancies in the

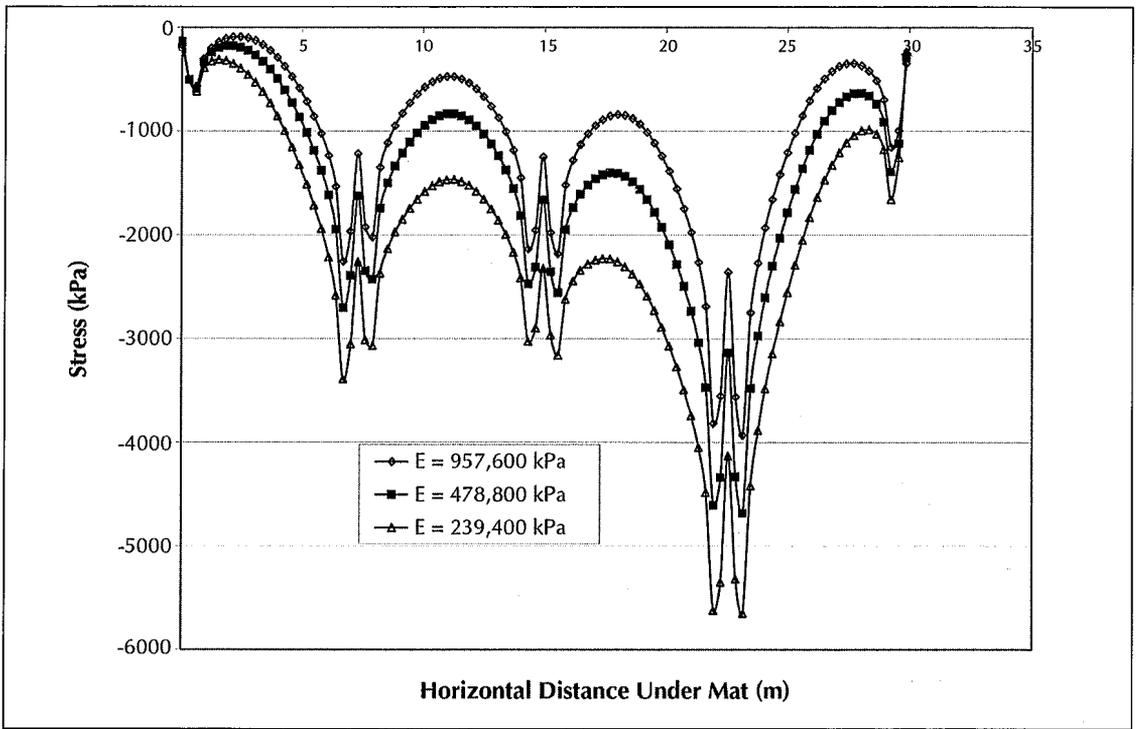


FIGURE 15. The effects of soil modulus on the bending stress 0.3 meters (1 foot) below the top of the mat foundation.

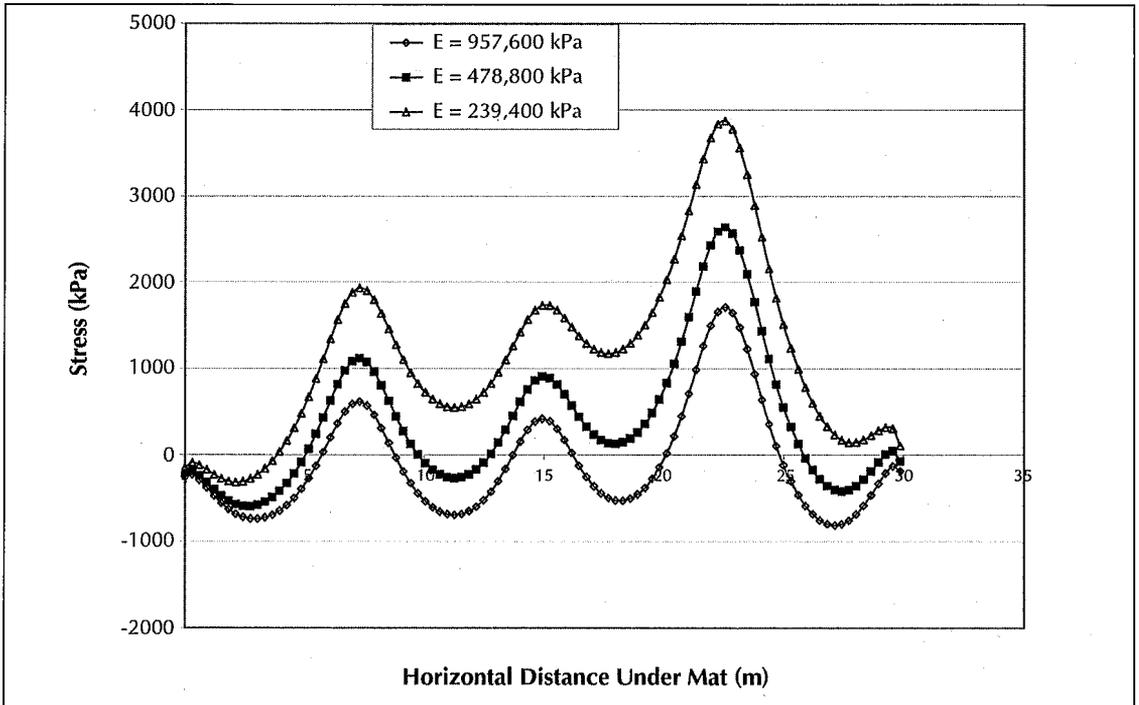


FIGURE 16. The effects of soil modulus on the bending stress 0.3 meters (1 foot) above the top of the mat foundation.

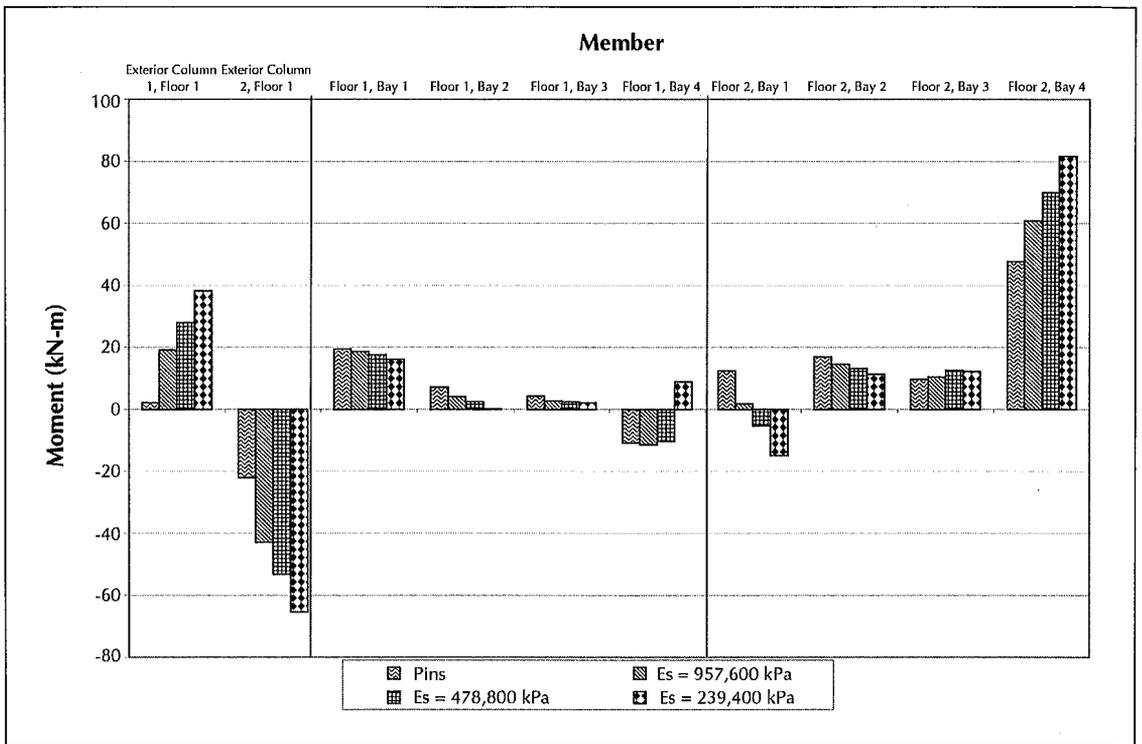


FIGURE 17. The effect of soil modulus on structural element bending moments.

structural load carrying system and considerations for the specific construction staging application of loads for the building.

Elastic-Plastic Analyses

The analyses of SSI described above have modeled the soil as a linear-elastic material. Some initial non-linear analyses utilized PLAXIS with a Mohr-Coulomb elastic-perfectly plastic soil failure criterion and interface elements that permit slippage between the soil and foundation wall when the interface strength is exceeded. Beam elements were used to simulate temporary excavation support and the excavation sequence was approximated. Because PLAXIS cannot model the structure in detail, the foundation-level column loads were first computed using the linear elastic ANSYS building-foundation-soil model of Figure 3 and then applied as input to the PLAXIS model. Table 4 shows the material properties for these analyses. Soil elements at the foundation-soil interface were assigned an interface strength equal to 0.7 of the soil strength. These elastic-perfectly plastic analy-

ses do not account for time-dependent soil behaviors such as consolidation, secondary compression or creep.

TABLE 4.
Material Properties for
PLAXIS Elastic-Plastic Analyses

Material	Property	Value
Soil	γ	20.4 kN/m ³ (130 pcf)
	ν	0.25
	E	478,800 kPa (10,000 ksf)
	ϕ	38
	c	0
Concrete	γ	23,6 kN/m ³ (150 pcf)
	ν	0.15
	E_c	27,770,400 kPa (580,000 ksf)

These initial analyses showed that the elastic-plastic vertical stresses are more uniformly distributed than the corresponding elastic values, with the greatest differences in the outer quarters of the foundation. The horizontal stresses and shear contact stresses are similarly affected. The elastic-plastic vertical displacements are about 25 percent greater than the equivalent elastic values of Figure 13. However, these initial studies (described in detail by Alonge⁴) have not investigated the effects of non-linear soil behavior on the stresses in the foundation mat or building frame.

Summary & Conclusions

A method was developed to model the effects of SSI for tall buildings using a two-dimensional finite-element model. In order to represent a three-dimensional structure in two dimensions, a unit-slice of the building was modeled. Continuous members (e.g., mat foundation, sub soils and floor slabs) required no scaling of material properties but the stiffness of discrete elements (e.g., beams and columns) was scaled over the entire bay spacing. A two-dimensional model would not be applicable for situations without symmetry in the third dimension.

This research has provided a comparison of two finite-element packages: ANSYS, a general-purpose finite-element analysis package, and PLAXIS, a package used for geotechnical engineering analysis. ANSYS provides a wide variety of options for the investigation of complex structural models and loading conditions. However, it is complicated to use, does not easily model the initial gravity body forces of geotechnical engineering problems and requires large amounts of computing power, file management and storage space. PLAXIS is much easier to use, has powerful automatic mesh generating capabilities and can easily model initial gravity body forces and non-linear soil behavior. However, PLAXIS cannot model complex structures and loadings in detail. Thus, the foundation-level column loads were first computed by ANSYS using the detailed linear elastic building-foundation-soil model (see Figure 3) and then applied as input loads to PLAXIS. The linear analyses

showed little difference between the contact stresses and foundation displacements computed by ANSYS and PLAXIS.

Analyses were performed on a structural model subjected to three foundation conditions:

- pin-connected to a rigid foundation base;
- pin-connected to a mat foundation bearing on the surface of a linear elastic soil; and
- pin-connected to a mat foundation embedded within a linear elastic soil.

The linear analyses demonstrated the effects of SSI on foundation settlements, foundation contact stresses and stresses in the foundation mat and bending moments in the building frame.

Foundation Embedment. The embedded foundation (see Figure 6) settled less than the surface foundation because of the net load reduction due to the weight of the excavated soil, the smaller thickness of soil beneath the foundation and the beneficial effects of confinement. The ANSYS computations show that horizontal contact stresses were greatly reduced for the embedded foundation because of load transfer into the building's below-grade foundation walls.

Stresses in the Foundation Mat. Bending stresses are proportional to the general shape of the mat foundation's bending moment diagram. Significant stress concentrations were computed at column locations in the concrete mat, compressive near the top of the mat (see Figure 8) and tensile near the bottom of the mat (see Figure 9). Compared to a 2.44-meter (8-foot) thick mat, a 1.83-meter (6-foot) mat produced slightly less uniform contact stresses (see Figure 7) and significantly greater stress concentrations (see Figures 8 and 9), but almost identical lateral deflection of the building centerline.⁴

Bending Moments in the Building Frame. Bending moments were computed at critical locations in lower floors of the building frame shown by Figure 10. In general, the moments in the structural members are not very different for the 2.44-meter (8-foot) and 1.83-meter (6-foot) mats. Figure 11 shows that an analysis in which the structure was

pinned to a rigid base underestimates the bending moments at the exterior columns of the first floor by a factor of 2 compared to the analysis with SSI.

Effects of Soil Modulus. A decrease in soil modulus from 957,600 kPa (20,000 ksf) to 239,400 kPa (5,000 ksf) produced more uniform vertical stress distributions with less pronounced stress concentrations beneath the columns (see Figure 12), proportional increases in building settlements (see Figure 13) and proportional increases in the building centerline deflection (see Figure 14). The compressive and tensile stress concentrations at the top and bottom of the concrete mat (see Figures 15 and 16) more than doubled with decreasing soil modulus. When the foundation and subsoil rigidity are not modeled (pinned condition) with the building, bending moments at the exterior columns and beams can be underestimated by factors of 2 to 3. Incorrect estimates of soil modulus can lead to large errors in the bending moments computed at critical locations.

Effects of Non-Linear Soil Behavior. The importance of modeling soil with a non-linear elastic-plastic failure criterion such as the Mohr-Coulomb elastic-perfectly plastic model was investigated. The elastic-perfectly plastic vertical stresses are more uniformly distributed than the corresponding elastic values and the elastic-plastic vertical displacements are about 25 percent greater than the equivalent elastic values. However, these initial studies have not investigated the effects of non-linear soil behavior on the stresses in the foundation mat or building frame.

Importance of SSI. This research shows that for the type of structure studied, it is important to include the effects of SSI in computing building response to the applied loads. In this example, the analyses of the building frame model pinned to a rigid base greatly underestimated the bending moments at the lower floors in the frame. The linear soil modulus will also greatly affect the stresses in the foundation mat and at column locations in the frame. The effects of non-linear soil behavior on the building structural response may also be important but they have not been quanti-

fied in the preliminary non-linear computations. These results show that it is important to model the foundation and deformable subsoils with the building structure in order to capture the effects of SSI on the building structural response. This requirement implies a need for improved coordination of both geotechnical and structural engineering research and design studies, including advances in finite-element software packages such as ANSYS and PLAXIS. Further studies are warranted to examine impact of construction staging as part of the SSI analysis. The net sum of this work is a better understanding of building behavior in comparison to traditional design methods, leading to more efficient structural designs.

NOTES — The finite-element software packages used for this study are ANSYS 5.5[3] and PLAXIS 7.1.1[7]. ANSYS, a general-purpose two- and three-dimensional finite-element program developed to analyze mechanical, thermal and structural problems, offers numerous elements and loading conditions. However, ANSYS does not automatically generate an initial geostatic stress-zero displacement condition. Rather, the initial stresses are calculated as the first of a number of load sequences and the displacements caused by the initial stresses must then be subtracted from the displacements computed for subsequent loadings in order to determine the net displacements caused by the non-geostatic loading. ANSYS was used to model the detailed structural response of the model fifty-story building to applied loads in a linear elastic analysis. PLAXIS, a two-dimensional (axisymmetric or plane strain) finite-element program, was developed for geotechnical applications. The program calculates initial geostatic stresses, considers the effects of gravity body forces and drainage conditions, and incorporates a number of non-linear stress strain models. PLAXIS operates through an easy-to-use graphical user interface and creates the finite-element model according to user-specified requirements. However, the element selection and loading conditions are too limited for the detailed analysis of building structures. PLAXIS was used for verification of the ANSYS computations and for an initial investigation on the effects of non-linear soil behavior on building structural response.



LEWIS EDGERS is a Professor at Tufts University, where he specializes in geotechnical engineering. He has earned degrees at Tufts and the Massachusetts Institute of Technology. He is a fellow of the American Society of Civil Engineers, past president of the Boston Society of Civil Engineers and is a registered engineer in the state of Massachusetts. His current research is in the areas of soil-structure interaction and rainfall-induced landslides.



MASOUD SANAYEI is a Professor of Civil and Environmental Engineering at Tufts University. He has been on the Tufts faculty since 1986 after graduating from the University of California at Los Angeles. He is the Chair of the ASCE Committee on Methods of Monitoring and Evaluating Structural Performance. Dr. Sanayei conducts research in the field of condition assessment of bridges, nondestructive testing, soil-structure interaction, floor vibrations testing and evaluations, structural dynamics and earthquake engineering.



JOSEPH L. ALONGE is currently a Geotechnical Engineer at Hardesty & Hanover, LLP. His responsibilities include the design and analysis of deep foundations for bridges and earth-retaining structures. He has worked in the field of Civil Engineering with involvement in site development projects. He holds a M.S.C.E from

Tufts University and a B.C.E from the Georgia Institute of Technology.

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