Example 6.3 Analysis of structure on nonlinear soil medium

1 Description of problem

An application of the proposed iterative procedure is carried out to study the behavior of foundation resting on nonlinear soil medium with considering influence of the superstructure rigidity.

The previous example shown in Figures 6.11 and 6.12 is also chosen here to show the analysis of structure on nonlinear soil medium with some modification to be a practical problem.

The floor is chosen to be a slab of 22 [cm] thickness resting on skew paneled beams. The slab carries a uniform load of 11.8 [kN/m^2]. Foundation is considered as a raft foundation with openings. The dimensions of paneled beams, columns and foundation are the same as those of the previous example.

2 Soil properties

Two different types of soil models are considered in this case-study:

- *Winkler*'s model that represents the subsoil by isolated springs
- Layered model that considers the subsoil continuum medium

The foundation is resting on a soil layer of 10 [m], overlying a rigid base. The soil types are represented by the modulus of elasticity E_s, for layered model that yields modulus of subgrade reaction k_s, for *Winkler*'s model. Table 6.7 shows two different soil types examined in this study according to the soil properties E_s and k_s. The two soil types are selected to represent weak and stiff soil. *Poisson*'s ratio is taken ν_s = 0.3 for the two soil types.

Table 6.7 Soil properties for two different soil types

Type of soil	k_s [kN/m^3]	E_s [kN/m^2]	q_{ult} [kN/m^2]
Weak soil	4000	18000	200
Stiff soil	40000	180000	400

3 Analysis

To show the difference between the results of linear and nonlinear analyses with and without interaction of superstructure for the two cases of soil models, the foundation is analyzed for both the two soil types four times as follows:

a) As a plate resting on linear soil medium without the effect of superstructure rigidity
b) As a plate resting on nonlinear soil medium without the effect of superstructure rigidity
c) As a plate resting on linear soil medium with the effect of superstructure rigidity
d) As a plate resting on nonlinear soil medium with the effect of superstructure rigidity

The raft foundation is divided into 504 square elements. Each element has the dimension of 1.25 [m] × 1.25 [m]. The typical floor is divided into 100 square plate elements. Each has dimensions of 1.0 [m] × 1.0 [m] to represent the floor slab. The plate elements are connected with 140 beam elements to represent the skew paneled beams.

For analyzing the foundation without interaction of the superstructure, the loads are obtained from floor reactions when analyzed as rested on fixed supports, Table 6.8.

Table 6.8 Loads on foundation without interaction of superstructure

Point	*a*	*b*	*c*	*d*	*e*	*f*
Load [kN]	480	1085	975	3000	2630	2270

The initial subgrade reactions k_{ti} for the continuum model are obtained from the linear analysis of foundation on Continuum model using Equation 6.24. For *Winkler*'s model, the initial subgrade reaction k_t is the same as that of the modulus of subgrade reaction k_s.

Because of the symmetry of structure in shape, load geometry and supporting soil about *x*- and *y*-axis, only one quarter of the structure is considered in the analysis.

4 Results and discussion

Figures 6.14 to 6.25 show the distribution of settlement, contact pressure and moment at section I for 16 cases of analysis. In general, it can be noticed from those figures for both models and types of soil that:

- The settlement values from nonlinear analysis with or without interaction of superstructure are greater than those obtained from linear analysis at any node on the raft

- The nonlinear analysis redistributes the contact pressure by decreasing its values under the columns and increasing the values at fields between columns. This makes the contact pressure approaches to the average pressure on the raft, especially for weak soil

- According to the redistribution of the contact pressure on the raft due to nonlinear analysis, the column moment is increased, while the field moment is decreased

- The maximum settlement, contact pressure and moment from the analysis with interaction of superstructure are less than those from the analysis without interaction

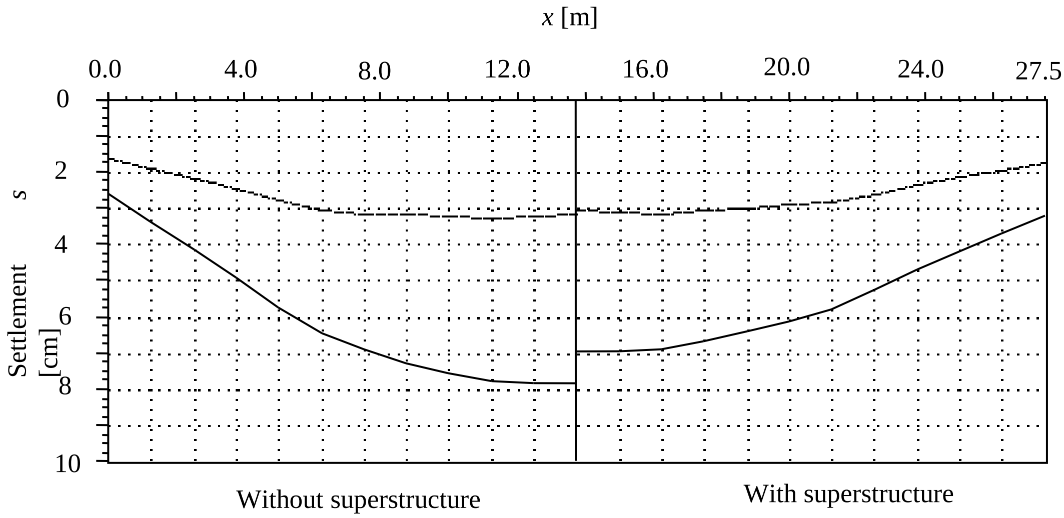

Figure 6.14 Settlement *s* [cm] at section I (*Winkler*'s model - weak soil)

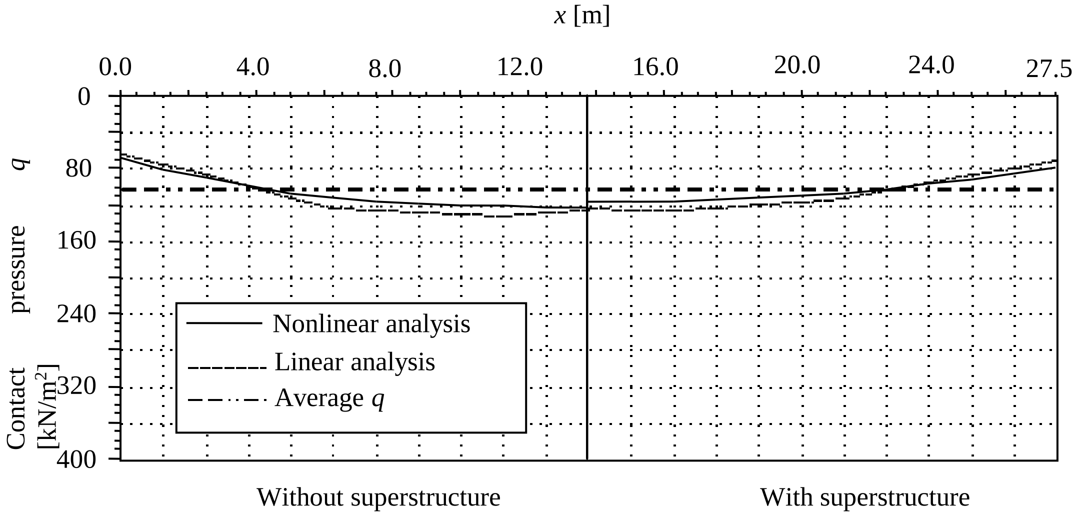

Figure 6.15 Contact pressure q [kN/m^2] at section I (*Winkler*'s model - weak soil)

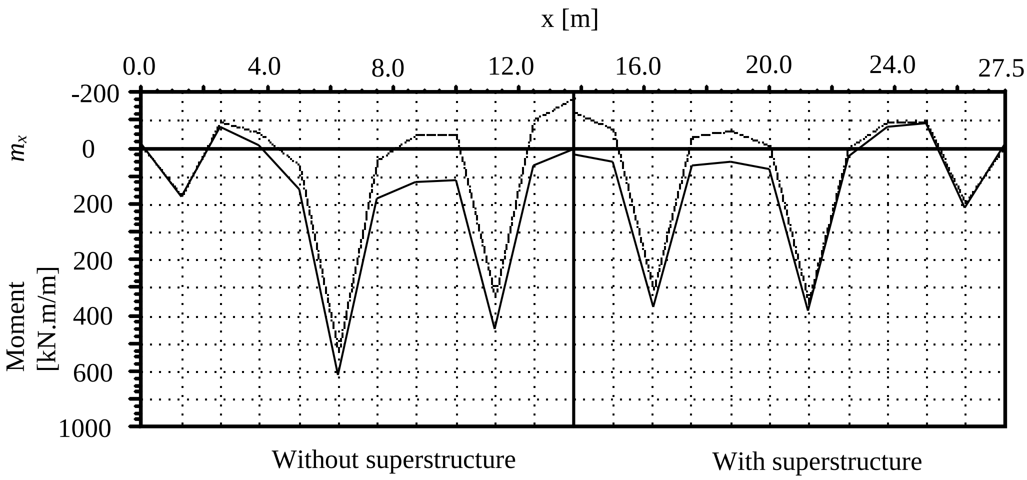

Figure 6.16 Moment m_x [kN.m/m] at section I (*Winkler*'s model - weak soil)

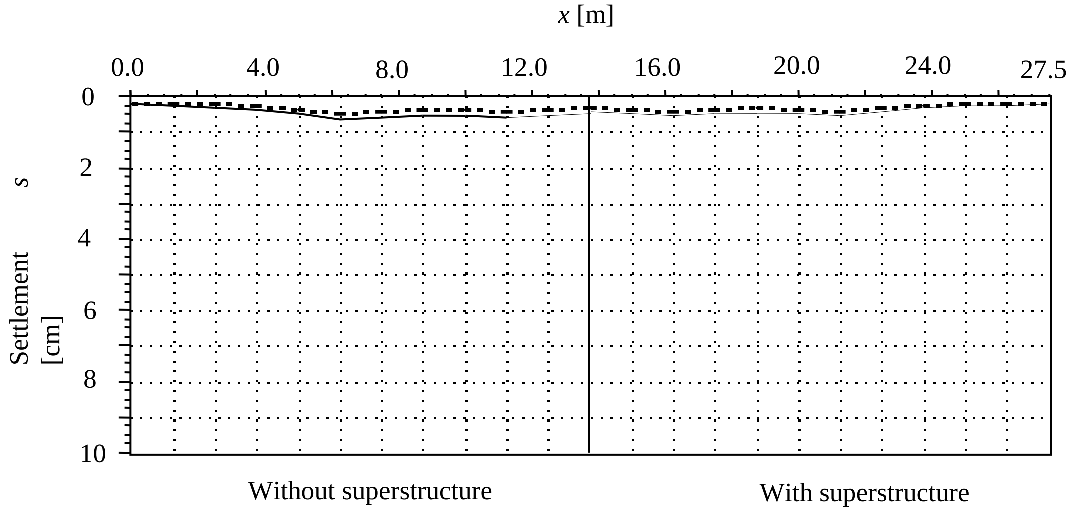

Figure 6.17 Settlement s [cm] at section I (*Winkler*'s model - stiff soil)

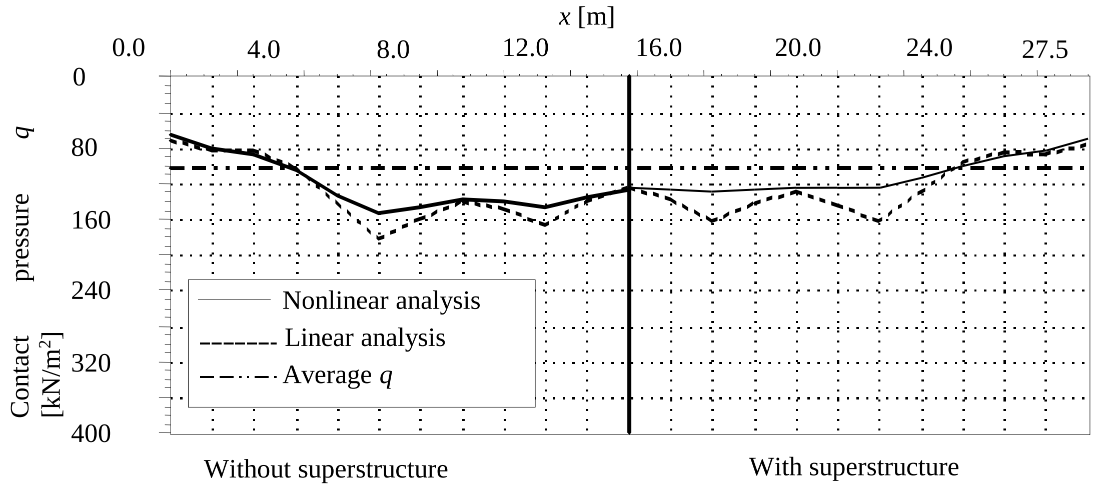

Figure 6.18 Contact pressure q [kN/m^2] at section I (*Winkler*'s model - stiff soil)

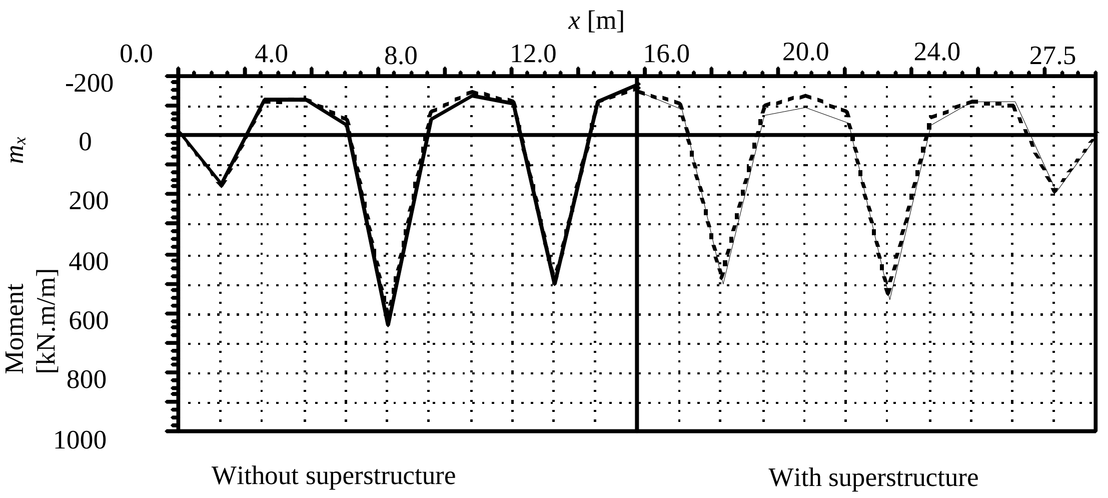

Figure 6.19 Moment m_x [kN.m/m] at section I (*Winkler*'s model - stiff soil)

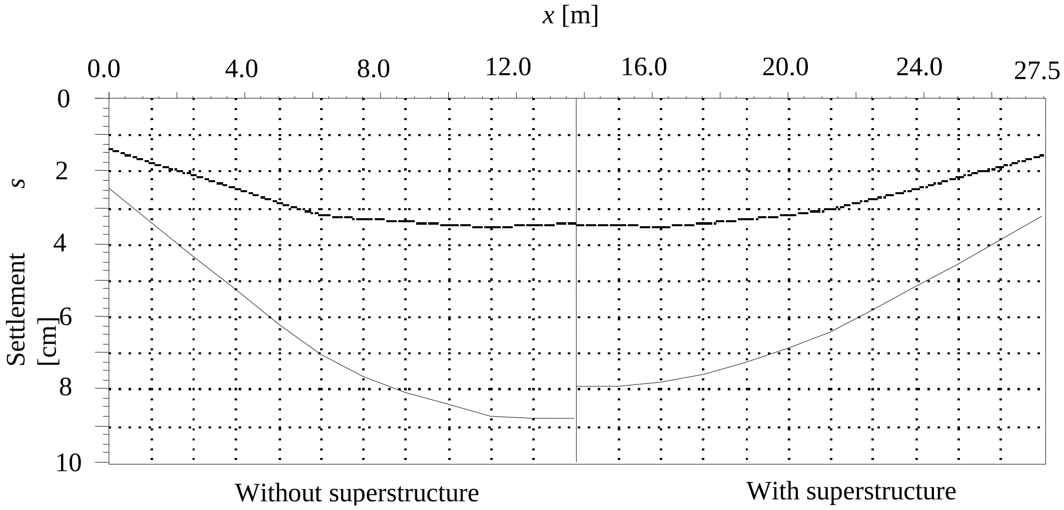

Figure 6.20 Settlement s [cm] at section I (layered model - weak soil)

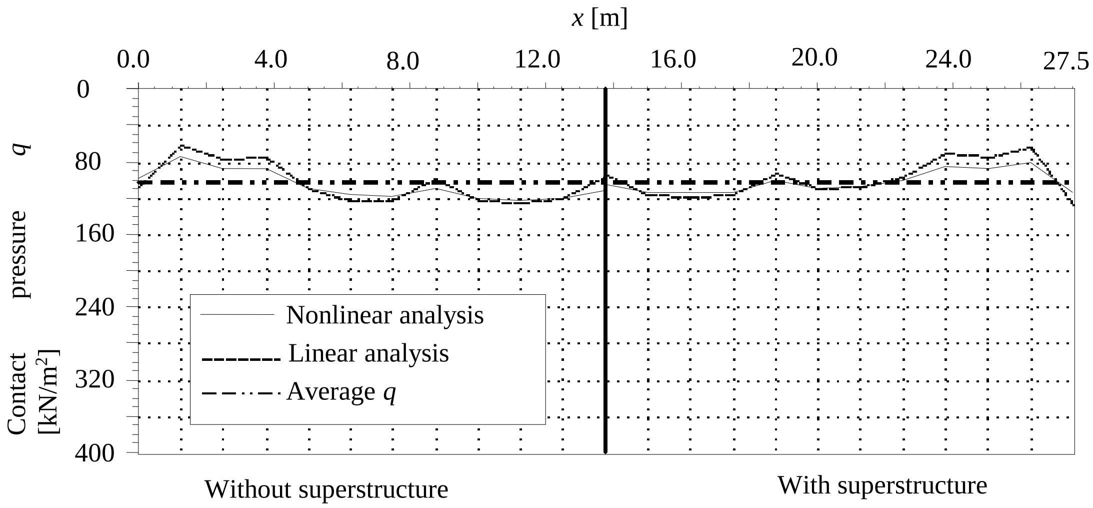

Figure 6.21 Contact pressure q [kN/m^2] at section I (layered model - weak soil)

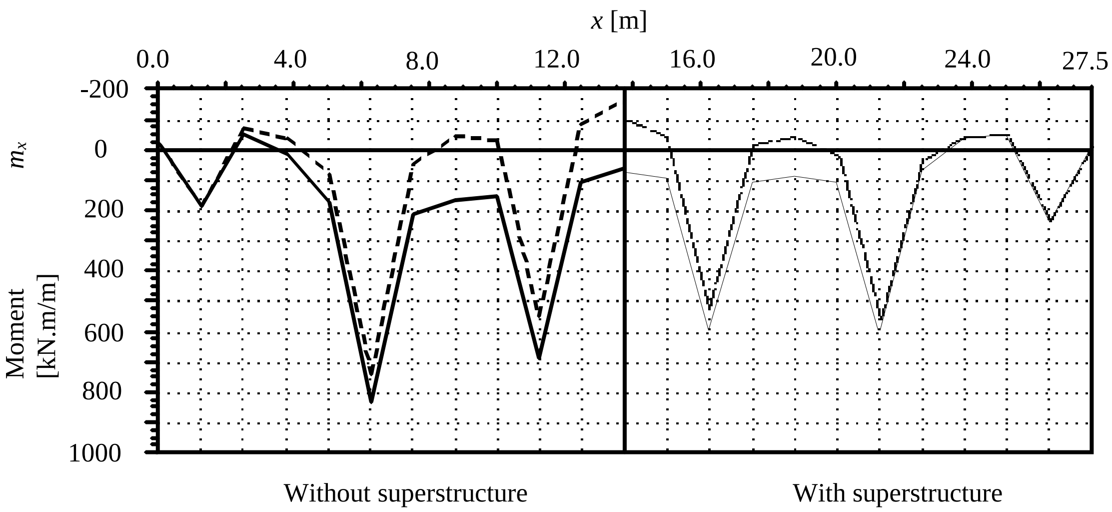

Figure 6.22 Moment m_x [kN.m/m] at section I (layered model - weak soil)

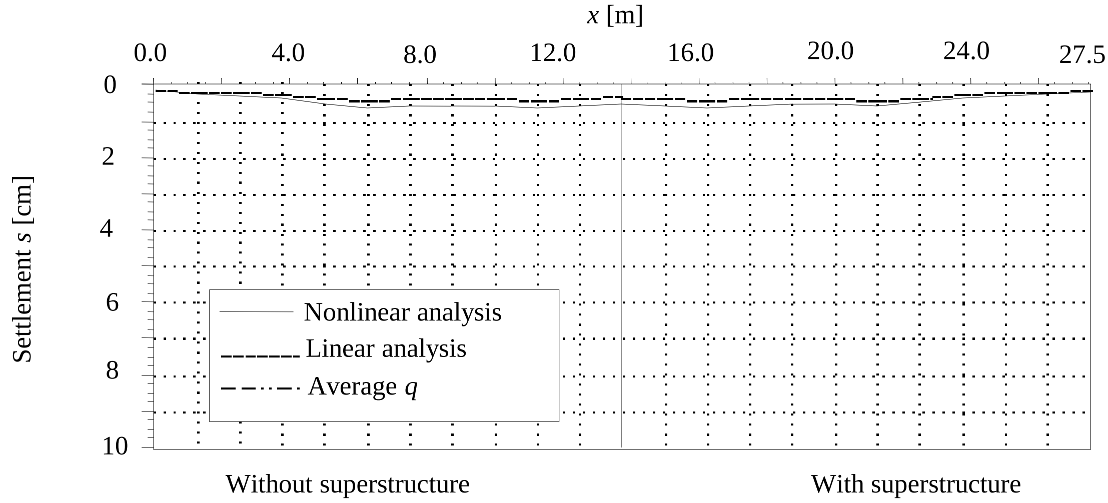

Figure 6.23 Settlement s [cm] at section I (layered model - stiff soil)

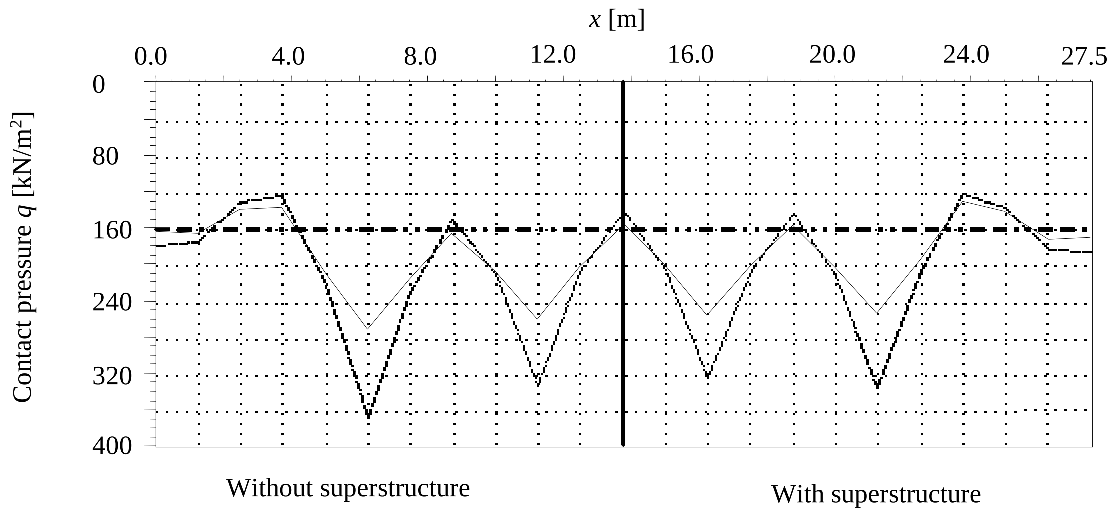

Figure 6.24 Contact pressure q [kN/m^2] at section I (layered model - stiff soil)

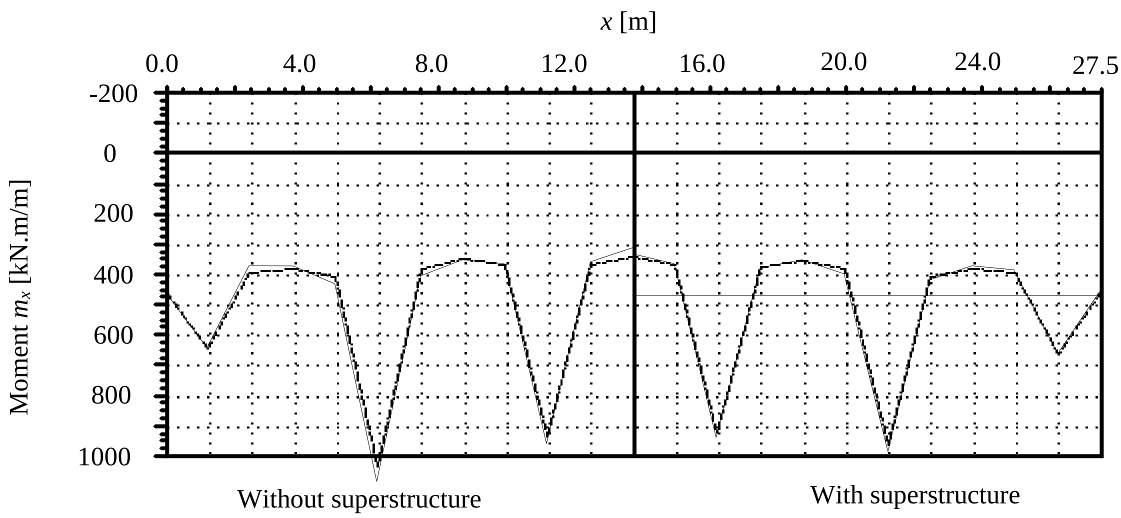

Figure 6.25 Moment m_x [kN.m/m] at section I (layered model - stiff soil)

The following Tables 6.9 to 6.12 show the maximum settlement, contact pressure under the columns, column moments and its differences Δ.

Table 6.9 Comparison of the maximum settlements max.s

Foundation-structure-interaction	Analysis of settlements	Settlements	weak soil E_s = 18000 [kN/m^2]		stiff soil E_s = 180000 [kN/m^2]	
			Winkler's model	Continuum model	*Winkler*'s model	Continuum model
without interaction	linear	s_{ln} [cm]	3.27	3.51	0.45	0.44
	nonlinear	s_{nl} [cm]	7.85	8.81	0.62	0.64
	$\Delta = 100 \times (s_{nl} - s_{ln}) / s_{ln}$ [%]		140	151	38	46
with interaction	linear	s_{ln} [cm]	3.15	3.50	0.41	0.42
	nonlinear	s_{nl} [cm]	6.94	7.93	0.54	0.58
	$\Delta = 100 \times (s_{nl} - s_{ln}) / s_{ln}$ [%]		120	126	32	38

Table 6.10 Comparison of the soil pressure q under the column

Foundation-structure-interaction	Analysis of settlements	Soil pressure	weak soil E_s = 18000 [kN/m^2]		stiff soil E_s = 180000 [kN/m^2]	
			Winkler's model	Continuum model	*Winkler*'s model	Continuum model
without interaction	linear	q_{ln} [kN/m^2]	131	126	182	310
	nonlinear	q_{nl} [kN/m^2]	122	122	152	212
	$\Delta = 100\times(q_{nl} - q_{ln}) / q_{ln}$ [%]		-7	-3	-17	-32
with interaction	Linear	q_{ln} [kN/m^2]	126	119	163	276
	nonlinear	q_{nl} [kN/m^2]	115	114	139	196
	$\Delta = 100\times(q_{nl} - q_{ln}) / q_{ln}$ [%]		-9	-4	-15	-29

Table 6.11 Comparison of the column moment m_x

Foundation-structure-interaction	Analysis of settlements	Column-moments	weak soil E_s = 18000 [kN/m^2]		stiff soil E_s = 180000 [kN/m^2]	
			Winkler's model	Continuum model	*Winkler*'s model	Continuum model
without interaction	linear	m_{ln} [kN.m/m]	725	742	609	557
	nonlinear	m_{nl} [kN.m/m]	812	836	638	613
	$\Delta = 100*(m_{nl} - m_{ln})/ m_{ln}$ [%]		12	13	5	10
with interaction	linear	m_{ln} [kN.m/m]	554	558	528	490
	nonlinear	m_{nl} [kN.m/m]	587	596	538	517
	$\Delta = 100*(m_{nl} - m_{ln})/ m_{ln}$ [%]		6	7	2	6

Table 6.12 Comparison of the field moment m_x

Foundation-structure-interaction	Analysis of settlements	Field-moments	weak soil E_s = 18000 [kN/m^2]		stiff soil E_s = 180000 [kN/m^2]	
			Winkler's model	Continuum model	*Winkler*'s model	Continuum model
without interaction	linear	m_{ln} [kN.m/m]	-184	-161	-162	-136
	nonlinear	m_{nl} [kN.m/m]	3.84	62	-178	-157
	$\Delta = 100\times(m_{nl} - m_{ln})/ m_{ln}$ [%]		102	139	10	15
with interaction	linear	m_{ln} [kN.m/m]	-125	-104	-153	-128
	nonlinear	m_{nl} [kN.m/m]	22	74	-159	-138
	$\Delta = 100\times(m_{nl} - m_{ln})/ m_{ln}$ [%]		118	171	4	9

Besides the above notes, the following results are reported (results are written without brackets for *Winkler*'s model, while in brackets ( ) for Continuum model):

Settlement (Table 6.9)

The maximum nonlinear settlement for weak soil exceeds maximum linear settlement by 140 [%] (151 [%]) and 120 [%] (126 [%]) for the analysis with and without interaction of superstructure, respectively, while for stiff soil by 38 [%] (46 [%]) and 32 [%] (38 [%]).

For both weak and stiff soil, the ratio between the maximum settlement from the analysis with interaction and that without interaction of superstructure is about 0.94 (0.97) for linear analysis, while this ratio decreases to 0.90 (0.90) for nonlinear analysis.

Contact pressure (Table 6.10)

The linear contact pressure for weak soil exceeds nonlinear contact pressure under the column by 8 [%] (4 [%]) for both analyses with and without interaction of superstructure, while for stiff soil by 16 [%] (31 [%]).

It is obvious that the contact pressure distribution patterns for *Winkler*'s model and Continuum model are not the same. The contact pressure under the columns for Continuum model are more than those of *Winkler*'s model by ratio of 1.7 for stiff soil. On the contrary to the case of stiff soil, this ratio is reduced to 0.95 for weak soil.

Moments (Tables 6.11 and 6.12)

For stiff soil, using either linear or nonlinear analysis the values of column moments are nearly the same. The difference between nonlinear and linear column moments does not exceed 5 [%] (10 [%]) and 2 [%] (6 [%]) for the analysis with and without interaction of superstructure respectively. This difference is slightly increased for field moments to 10 [%] (15 [%]) and 4 [%] (9 [%]).

For weak soil, there is also no significant change between linear and nonlinear column moments. But for field moments the difference between nonlinear and linear is 102 [%] (139 [%]) and 118 [%] (171 [%]) for the analysis with and without interaction of superstructure respectively. The results at section I also show that the field moment has changed from negative to positive at fields between columns due to the nonlinear analysis of the foundation.