Example 5.4 Comparison between raft and grid foundations

1 Description of the problem

El Arabi/ El Gendy (2001) examined the structural analysis and design of the three common foundation systems: raft, grid and isolated footings. They carried out the examination to evaluate the different types of structural systems in order to decide the most suitable ones for a specific situation. Here, an example is chosen from the above study with some modifications. Consider the foundation system shown in Figure 5.22, which may be designed as raft or grid. The raft dimensions are 30.5 [m] × 30.5 [m] while the overall grid dimensions are 33.0 [m] × 33.0 [m], with a constant strip width in both directions. The foundation carries 49 column loads, which are equally spaced, 5.0 [m] apart, in each direction. Column loads and the arrangement of columns are shown also in Figure 5.22.

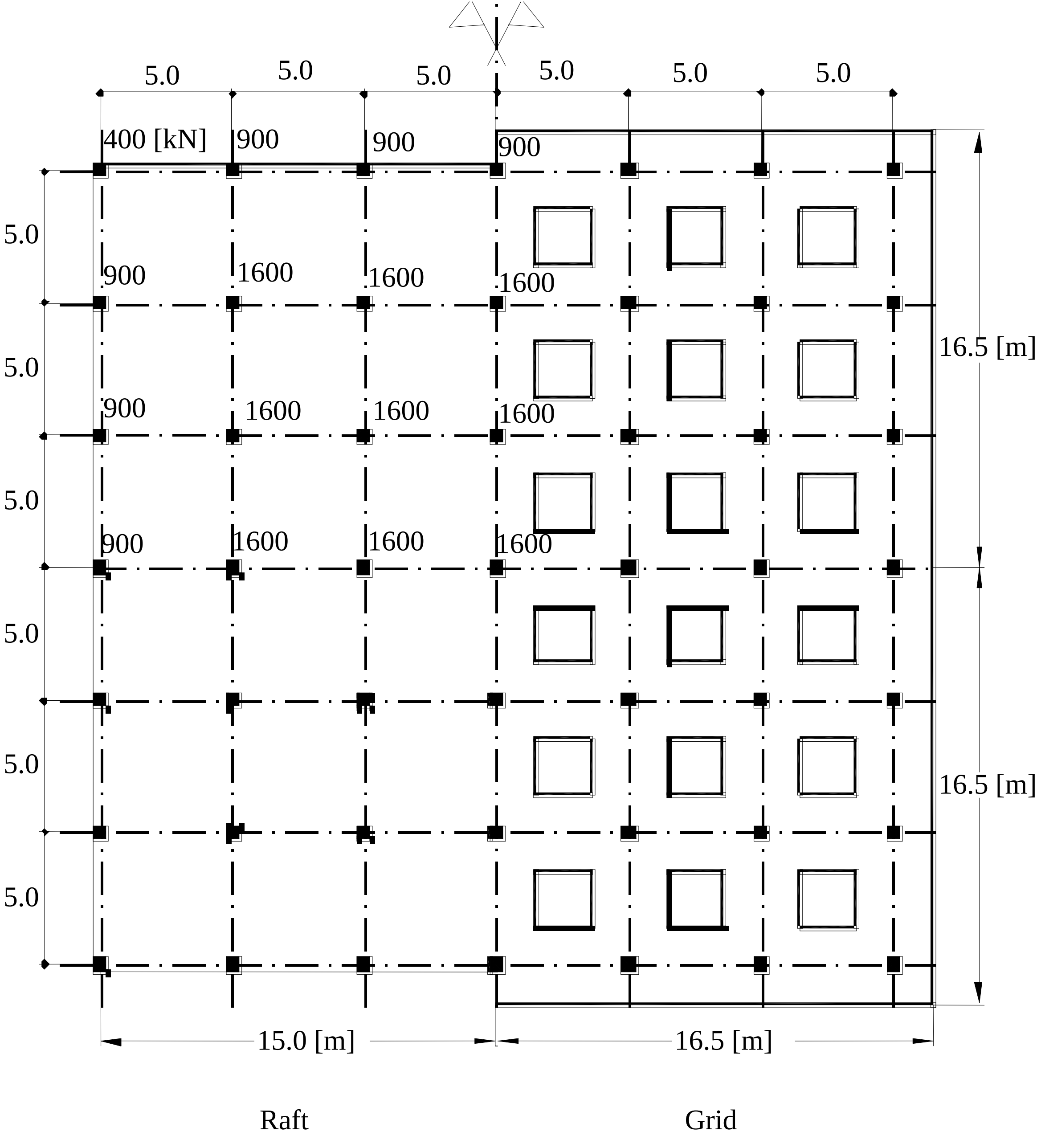

Figure 5.22 Foundation systems under consideration with loads

Both the raft and grid have the same uniform thickness *d*. The two foundations have the same contact area and column loads. Consequently, they will have the same average contact stress. Results are presented as functions of the ratio d/l, where l is the span between columns. For the sake of comparison, the volume of reinforced concrete of the entire foundation system whether raft or grid is kept unchanged.

2 Concrete material

The raft and grid are analyzed and designed for the following material parameters:

Concrete grade	*C* 200	
Steel grade	*S* 36/52	
Concert cube strength	$f_{cu} = 200$	[kg/cm^2]
Compressive stress of concrete	$f_c = 8$	[kg/cm^2]
Tensile stress of steel	$f_s = 1800$	[kg/cm^2]
Young's modulus of concrete	$E_b = 2 \times 10^7$	[kN/m^2]
Poisson's ratio of concrete	$\nu_b = 0.20$	
Unit weight of concrete	$\gamma_b = 0.0$	[kN/m^3]

Unit weight of concrete is chosen $\gamma_b = 0.0$ to neglect the own weight of the foundations.

3 Soil properties

The effect of the soil type is represented by changing the modulus of compressibility E_s. *Poisson*'s ratio and the unit weight of the soil are taken as $\nu_s = 0.3$ and $\gamma_s = 18$ [kN/m^3] respectively for all soil types. Four different soil types are examined according to the soil elastic parameter E_s, in which E_s = 5, 10, 20, and 40 [MN/m^2]. The thickness of the soil layer is considered according to the limit depth of the soil layer.

4 Results and analysis

It should be noticed that each of the two structural systems described above is valid as a foundation system for the problem under consideration. The raft and grid have the same average contact pressure on the soil, $q_{av} = 64$ [kN/m^2] and the same loading system. Accordingly, their contact areas are equal, $A_r = 930.25$ [m2]. Although the allowable bearing capacity (equal to average contact pressure) is always used to determine the foundation area, the maximum permissible settlement s_{max} all over the foundation governs the allowable bearing capacity of the soil, especially for great foundation such as in this example.

The analysis is carried out to study the effects of soil type and foundation thickness on the foundation behavior. The main results are the system rigidity, soil settlement, differential settlement, angular distortion, bending moments and the optimal thickness of foundation. A detailed description of the influence of each parameter is discussed in the following sections.

4.1 Limit depth t_s

The level of the soil under foundation at which no settlement occurs or the expected settlement will be very small where it can be ignored is defined as the limit depth of the soil. In this example, the limit depth is chosen to be the level at which the stress in the soil σ_E, resulting from the foundation pressure at the contact surface with soil, reaches the ratio $\xi = 0.1$ of the initial vertical stress σ_V. The stress in the soil σ_E is determined at the center of the foundation. As mentioned before, the average stress resulting from the foundation pressure at the surface is σ_o = 64 [kN/m2] for both the raft and grid (own weight of foundation is neglected). Results of the limit depth calculation are shown graphically in Figure 5.23. The computed limit depth is t_s = 19.53 [m] for raft and t_s = 18.93 [m] for the grid under the ground surface. Figure 5.23 also shows that the stress on the soil due to the grid is less than that of the raft. This is because the grid foundation has a wider extension at the contact surface with the soil associated with many unloaded spots among the grid strips. The interaction between the stress fields in this case leads to better stress distribution in the subsoil than the case of raft foundation. Accordingly, it can be said that the grid system might give better solution when the building is constructed on a ground that contains weak soil layers at a relatively deep level. Moreover, the discontinuity of the grid system allows for drainage at the ground surface, which can lead to better consolidation behavior if a clay layer exists under the foundation. In such circumstances, it is recommended to investigate the settlement behavior of the system.

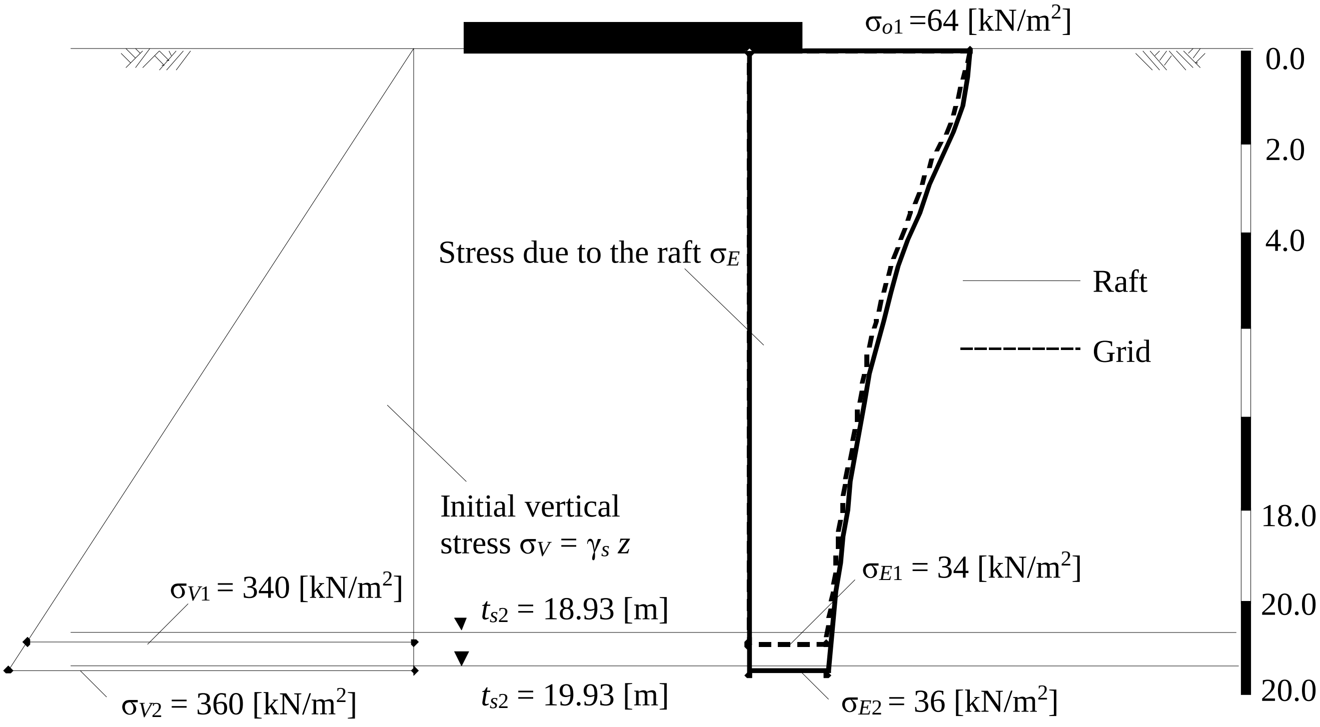

Figure 5.23 Limit depth t_s of the soil under both the raft and grid

4.2 System rigidity

Figures 5.24, 5.25 and 5.26 show the variation of the parameter k_r with the ratio d/l for raft and grid at the center for different soil types. From those figures, it is clear that all systems become more rigid for all types of soil as the foundation thickness increases. The foundation contribution into the whole system rigidity becomes higher as the soil becomes weaker. For instance, a raft of 90 [cm] thickness (d/l = 0.18) Figure 5.24, gives a rigidity parameter for the raft k_r = 62, 66, 76, and 83 [%] for E_s = 40, 20, 10 and 5 [MN/m^2] respectively while for the grid gives k_r = 35, 41, 48, and 59 [%] for E_s = 40, 20, 10 and 5 [MN/m^2] respectively. It is also clear that, as the soil becomes weaker as the foundation thickness for a given rigidity, k_r becomes smaller. Figure 5.26 shows a comparison between the rigidity parameters k_r for the raft and grid systems when E_s = 10 [MN/m^2]. It can be seen that for the same type of soil and a given depth ratio d/l, the raft gives maximum system rigidity if compared with the grid. The difference in rigidity between the two systems is about 25 [%] for all values of the ratio d/l.

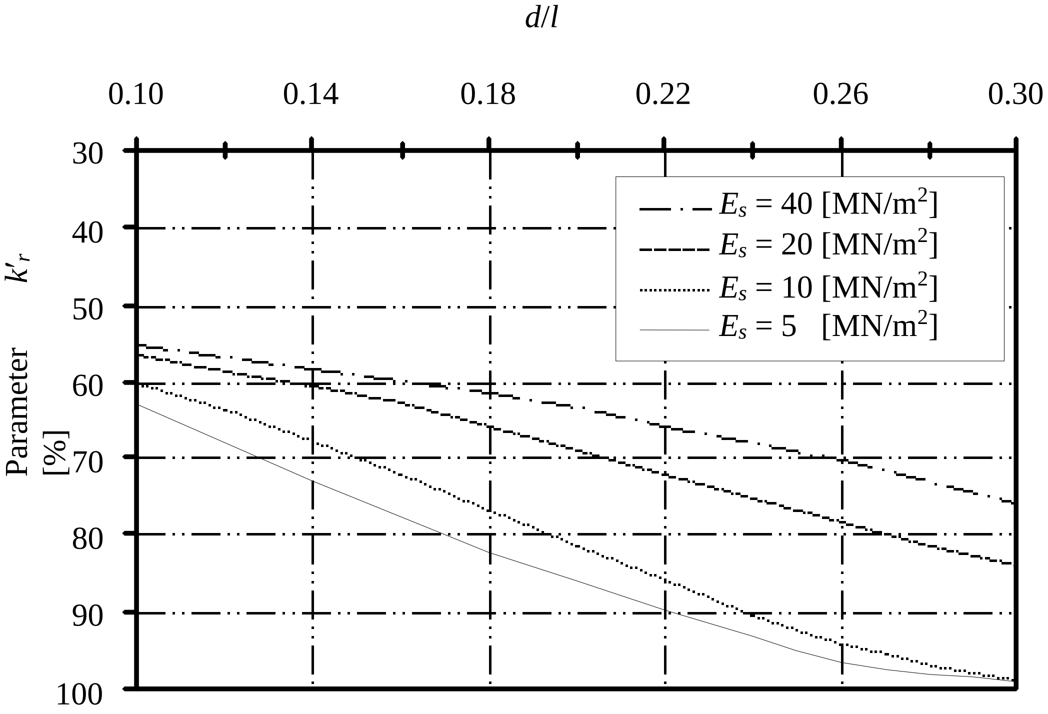

Figure 5.24 Variation of k_r at the center of the raft with the ratio d/l for different soil types

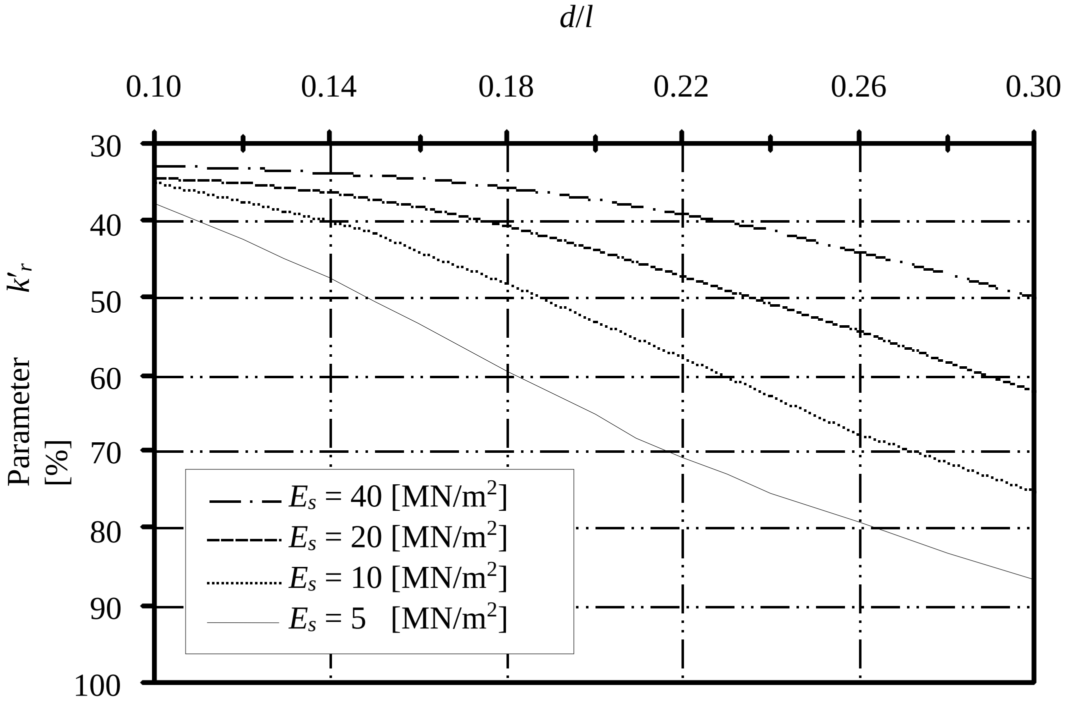

Figure 5.25 Variation of k_r at the center of the grid with the ratio *d*/*l* for different soil types

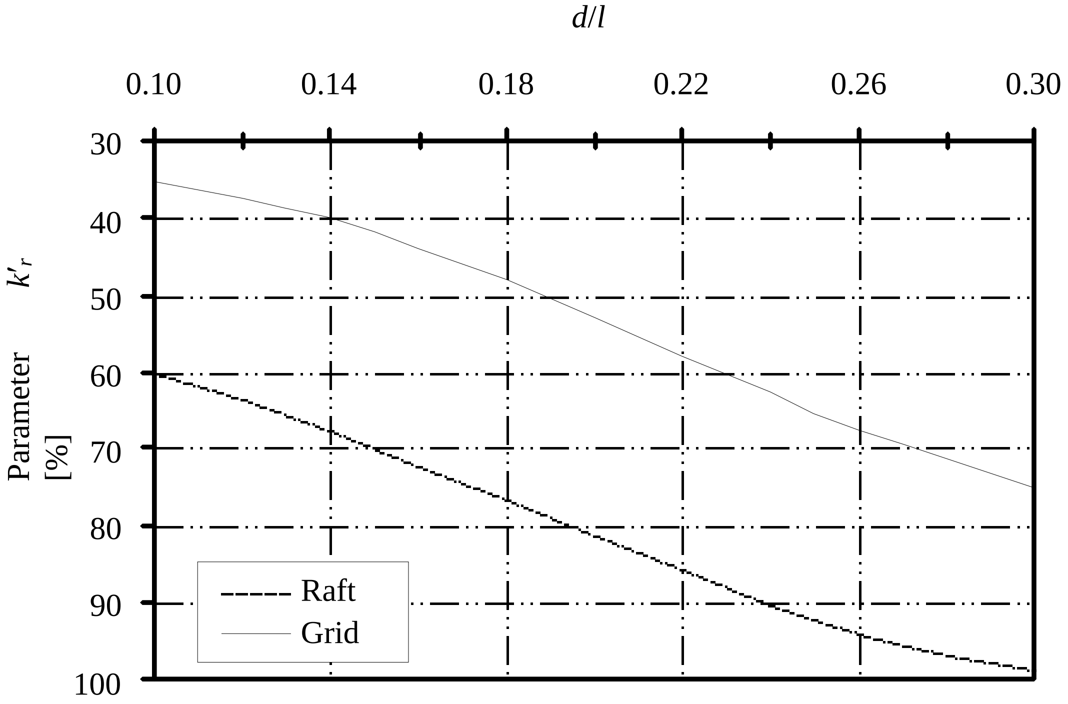

Figure 5.26 Variation of k_r at the foundation center with the ratio *d*/*l* for soil of E_s = 10 [MN/m^2]

4.3 Differential settlement and soil settlement

The influence of foundation rigidity and the soil type on the settlement is given in Figures 5.27 to 5.30. In Figure 5.27 and 5.28, the maximum differential settlements between adjacent columns are plotted as functions in the ratio *d*/*l* for the two different foundations. Figures 5.29 and 5.30 show, respectively, maximum differential settlements and the central settlement for raft and grid when the soil has E_s = 10 [MN/m]. It can be seen that the differential settlement decreases with the increase of foundation thickness for the two types of foundations, especially for weak soil. As it is expected, the weaker the soil, the bigger is the differential settlement. Raft system is the most efficient system in resisting the differential settlement and declining the settlement. The difference between the deferential settlement of the raft and that of the grid decreases when the foundation thickness increases. Figure 5.30 shows that the difference between the central settlement of the raft and that of the grid is about 0.7 [cm] for all ratios *d*/*l*.

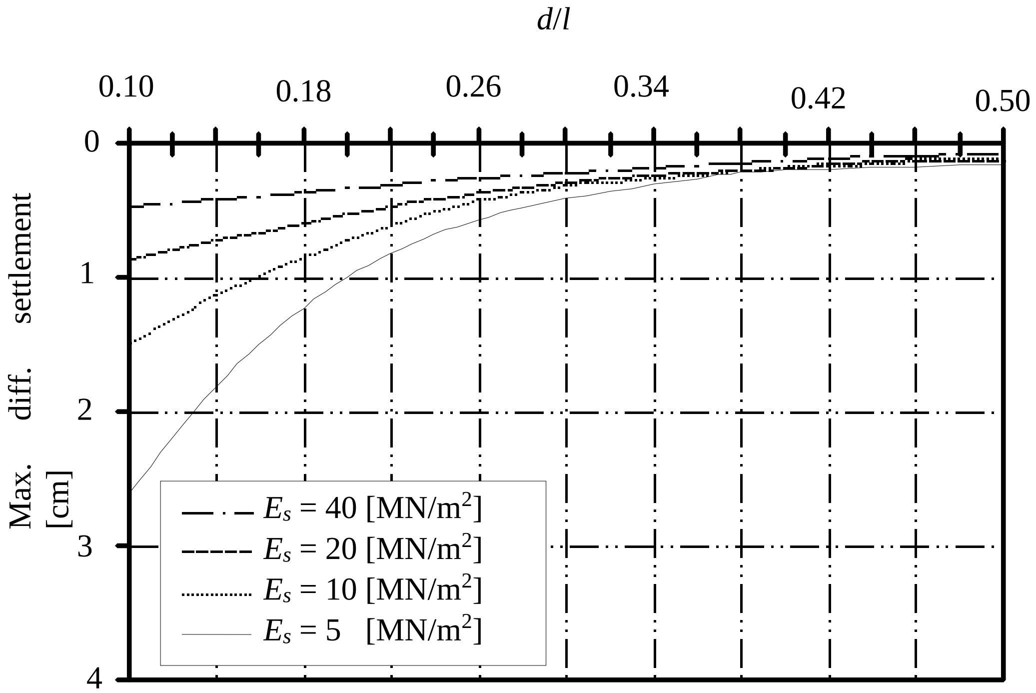

Figure 5.27 Maximum differential settlement between adjacent columns with the ratio *d*/*l* for the raft

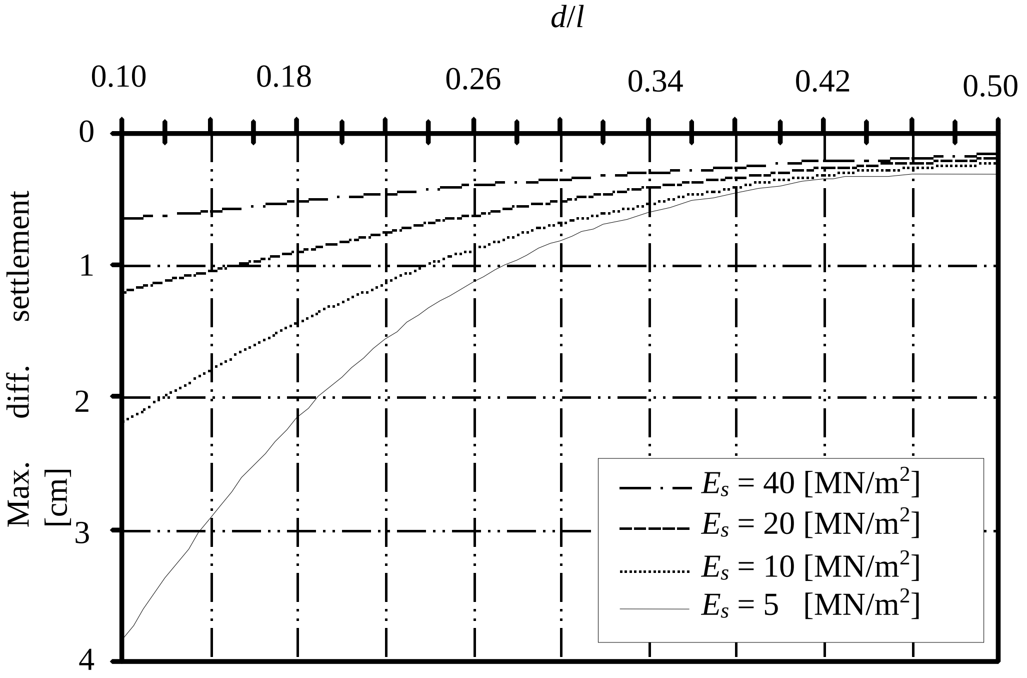

Figure 5.28 Maximum differential settlement between adjacent columns with the ratio *d*/*l* for the grid

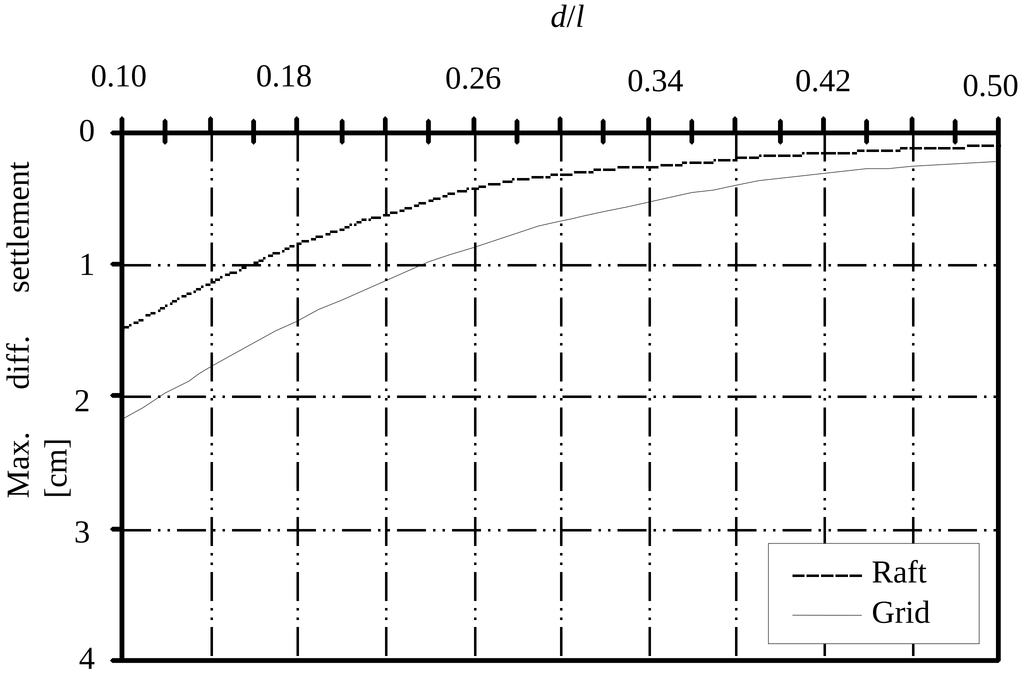

Figure 5.29 Maximum differential settlement between adjacent columns with the ratio *d*/*l* for soil of E_s = 10 [MN/m^2]

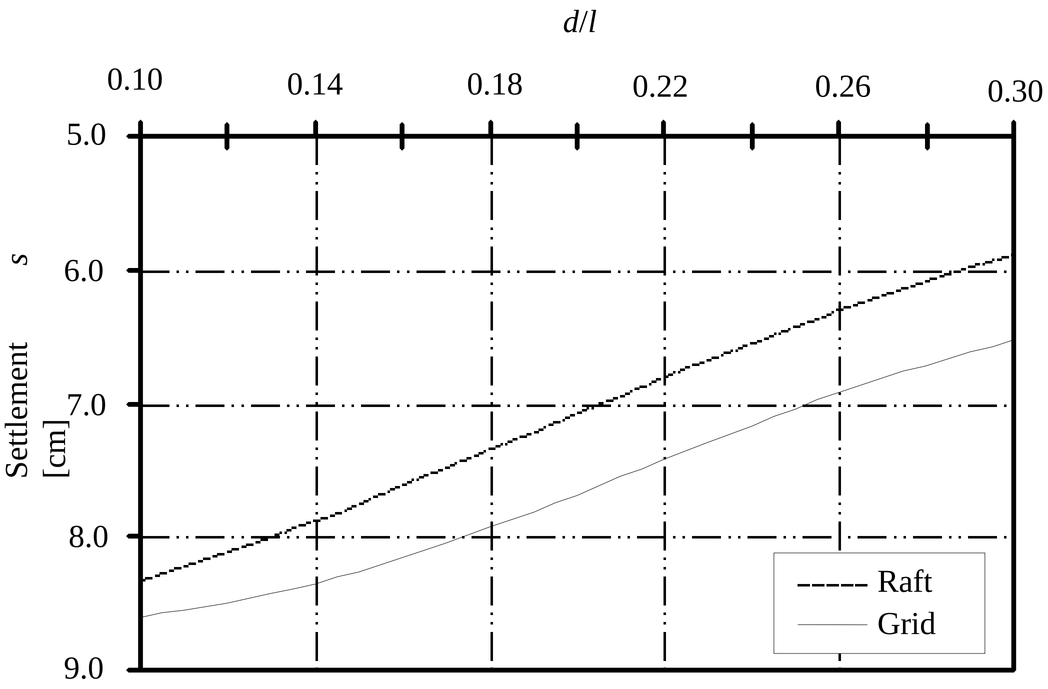

Figure 5.30 Settlement at foundation center with the ratio d/l for soil of $E_s = 10$ [MN/m^2]

4.4 Angular distortion

In this analysis, the angular distortion $1/L_{ij}$ between any two nodes i and j on the foundation is defined according to *Hemsley* (1998) as

$$\frac{1}{L_{ij}} = \frac{\left\| s_i - s_j \right\|}{L_{ij}} \tag{5.1}$$

where:

s_i and s_j	Nodal settlements
l_{ij}	Distance between the nodes i and j

Relative to any "primary node" i ($1 \leq i \leq n$), it is a simple matter to scan all the remaining (n - 1) nodes on the surface element mesh to locate the "secondary node" j associated with the maximum angular distortion. This procedure is repeated for each node in the mesh to give n values of maximum distortion, denoted by $1/L_n$.

Figures 5.31 and 5.32 show the contour lines of nodal angular distortion $1/L_{ij}$ for raft and grid for different soil types. Moreover, a comparison between the limiting contour values for raft and grid is given in Table 5.3. The thickness of the raft and grid is d = 0.5 [m]. For the same soil conditions, the angular distortion is more considerable in the grid if compared with the raft. The stiffening effect of ribs reduces the grid distortion as can be seen clearly from Table 5.3.

Table 5.3 Maximum and minimum contour values for raft and grid

Foundation system	Contour values of angular distortion reciprocal ($1/L_{ij}$)							
	E_s [kN/m^2]							
	5000		10000		20000		40000	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
Raft	220	150	410	270	775	500	1500	800
Grid	165	115	310	210	625	400	1250	700

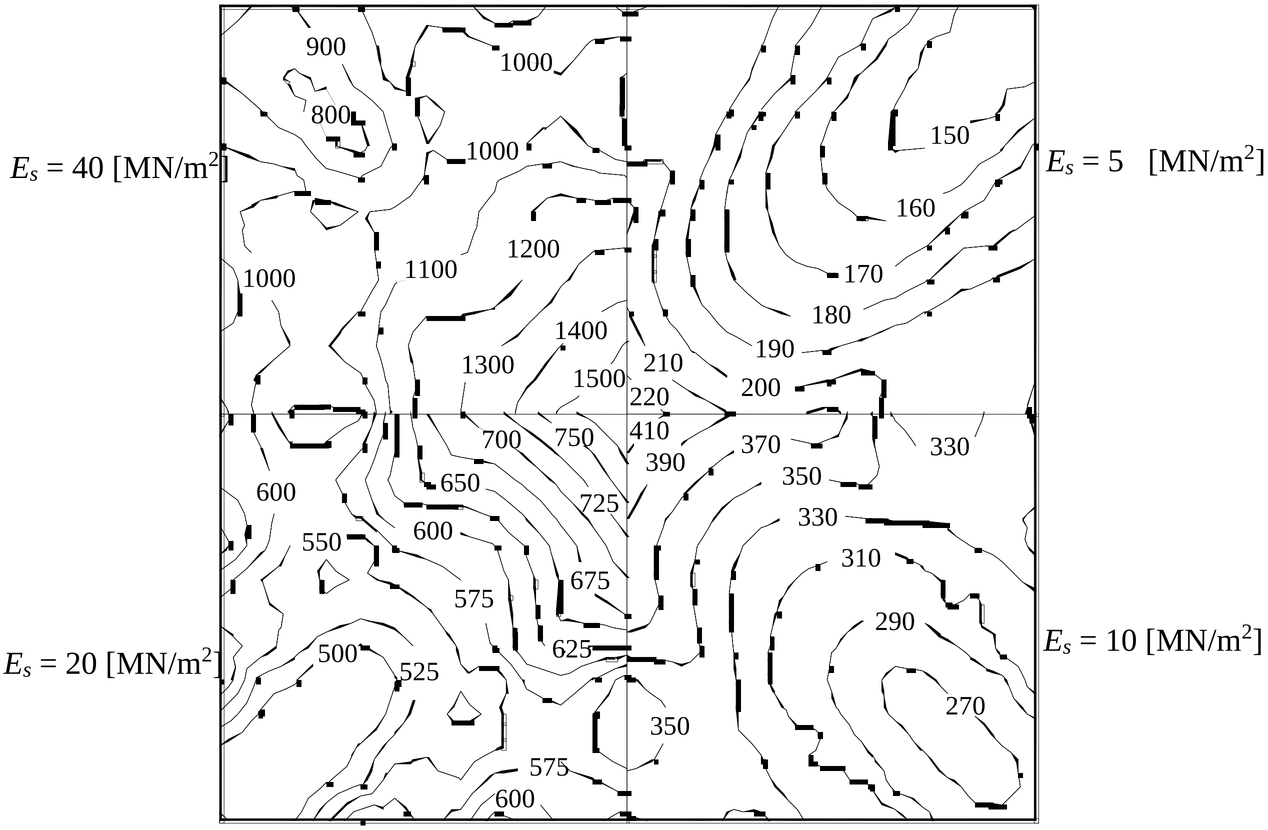

Figure 5.31 Contour lines of nodal angular distortion for a raft of 0.5 [m] thickness

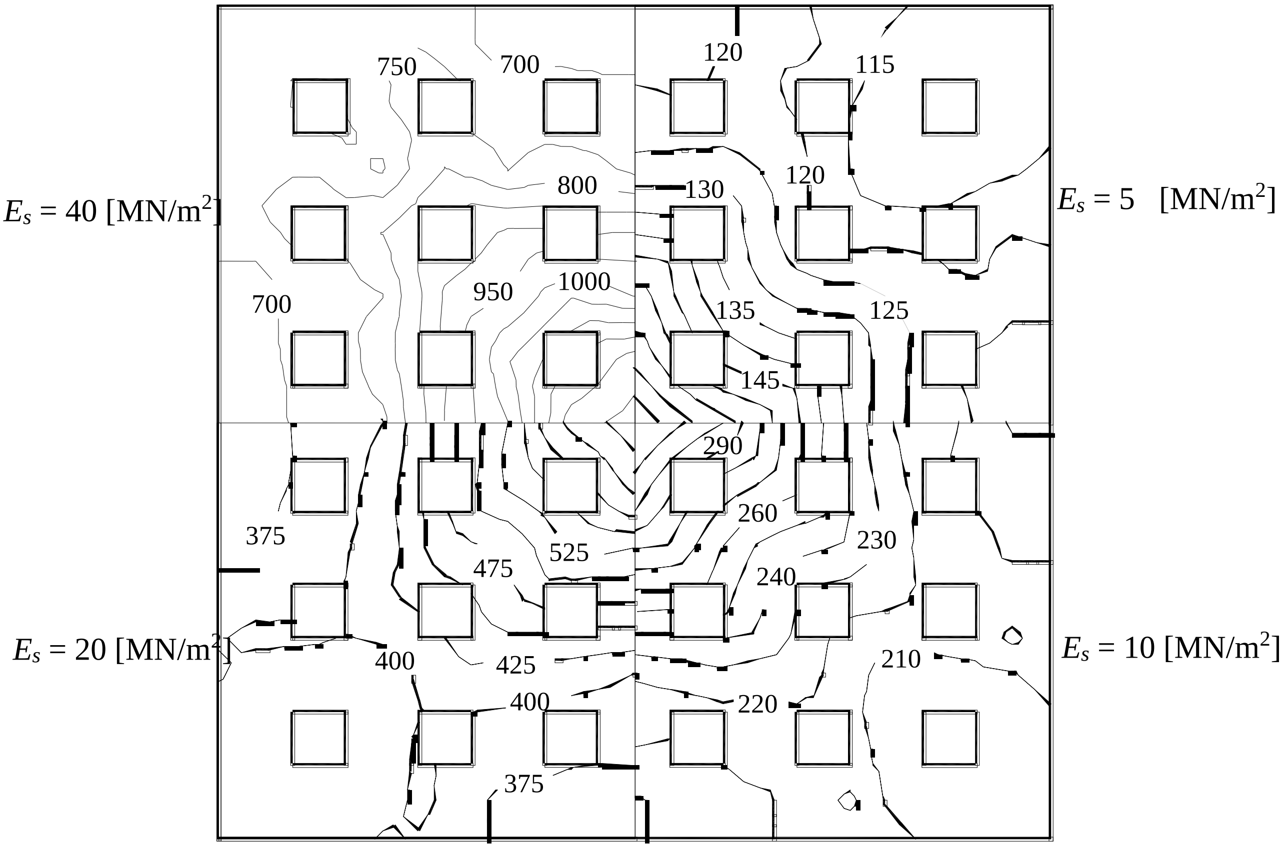

Figure 5.32 Contour lines of nodal angular distortion for a grid of 0.5 [m] thickness

4.5 Optimal thickness

In this study, the optimal thickness is defined as the minimum thickness of foundation for which the concrete section and tensile reinforcement are enough to resist the flexure moments without compressive reinforcement. The optimal design of reinforced concrete sections is based on the provisions of ECP 464 (1989) for working stress method. In this case, the maximum moment M_{max} and the sustained moment Ma for the system under consideration are calculated for different values of the thickness t ($t = d + 5$ [cm] cover). The maximum moment M_{max} resulting in the foundation is obtained from foundation analysis.

The sustained moment M_a for singly reinforced section according to working stress method is obtained from

$$M_a = \frac{(t-c)^2 \, B}{k^2_1} \qquad (5.2)$$

where:

c Concrete cover plus the radius of reinforcement bars

B Width of the section to be designed

k_1 Coefficient for design of singly reinforced sections as given by code

The minimum thickness of foundation is obtained when both moments M_{max} and M_a are equal. The optimal thickness of raft and grid is designed for the maximum moment obtained from the analysis. The maximum moment M_{max} and the sustained moment M_a are calculated for the raft and grid at different values of the foundation thickness and for various types of soil. Sustained moments are calculated according to the working stress method of ECP 464 (1989). The Results are given in Figures 5.33 and 5.34. According to the results, the bending moments increase as the foundation thickness increases and as the soil stiffness decreases as well. This is because the layered model used in the analysis strongly depends on the soil properties.

The optimal thickness of raft and grid resting on different types of soil can be obtained from Figures 5.33 and 5.34 respectively. For a given soil, the optimal thickness is when the thickness corresponds to the intersection of two curves: the optimal moment curve and the moment curve representing the given soil. It is clear that the optimal thickness of either raft or grid increases as the soil stiffness decreases. Unless it is essential, an unnecessary increase in the foundation thickness is not preferred as it attracts more bending moments and gives more costly design.

For the problem under consideration when E_s = 5 [MN/m^2], Figures 5.33 and 5.34 show that the working optimal depths of raft and grid are respectively about 0.85 [m] and 0.95 [m], keeping in mind that l = 5.0 [m]. This means about 11 [%] material saving for the raft than that for the grid because both foundations have the same contact area. Furthermore, Figures 5.24, 5.25, 5.27, and 5.28 show that the rigidities of raft and grid are 80 [%] and 63 [%], and the corresponding maximum span distortions are about 0.0028 and 0.004, respectively. Therefore, one can say that raft present the most appropriate solution for weak soil conditions.

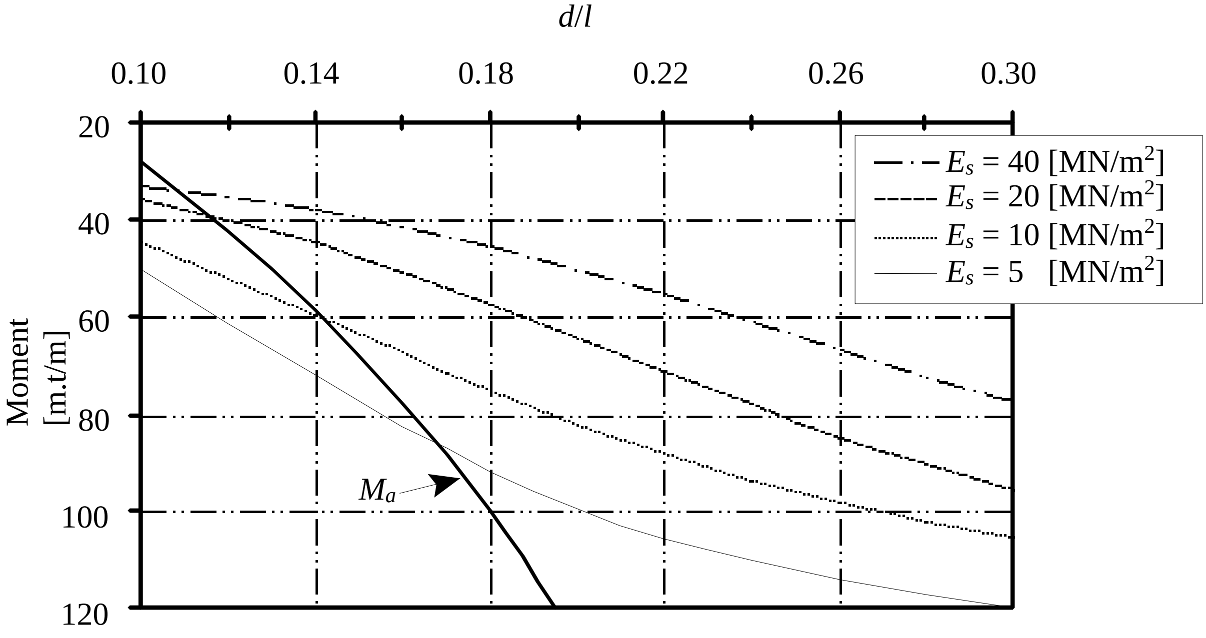

Figure 5.33 Determination of optimal thickness of the raft

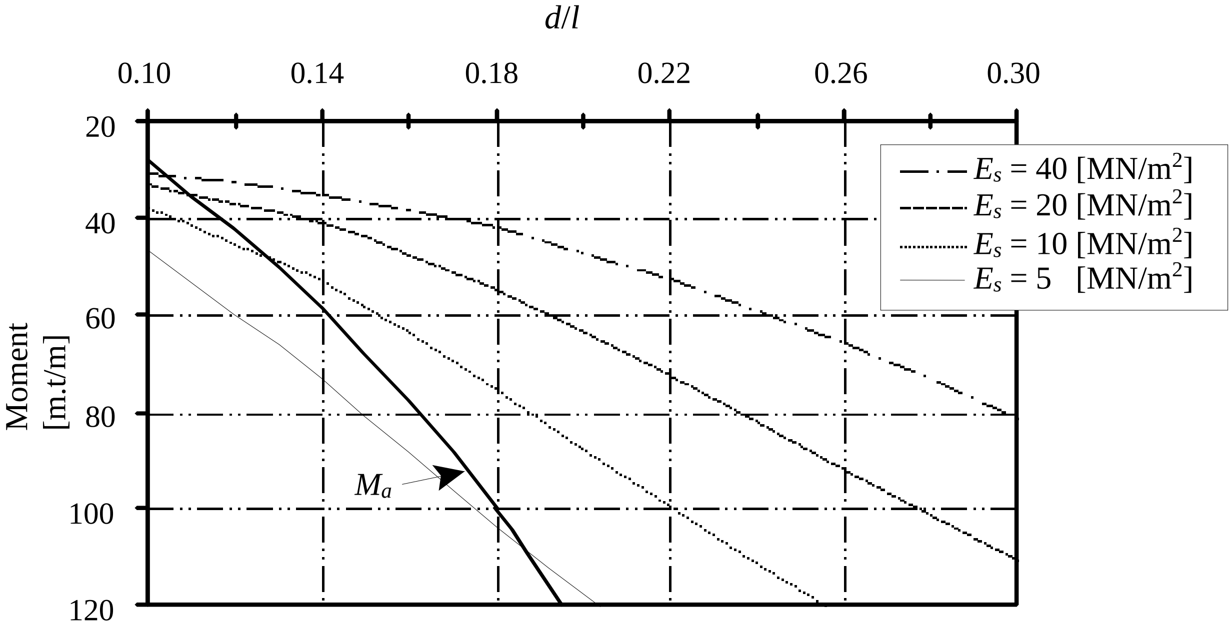

Figure 5.34 Determination of optimal thickness of the grid

5 Recommendations for foundation systems selection

Based on the analysis and results discussed before, Table 5.4 gives some recommendations that can put the designer on the economic side and help him to choose an appropriate foundation system for certain soil foundation conditions.

Table 5.4 Selection between raft and grid

Case of selection	Suitable foundation system	
	Raft	Grid
Soil has $E_s \geq 20$ [MN/m^2]	---	x
Soil has $E_s < 20$ [MN/m^2]	x	---
Weak layer at relative deep level ($z > 0.8\ t_s$)	---	x
Consolidated layer under foundation	---	x
Column span exceeds six times foundation thickness	x	---
Column span less than six times foundation thickness	x	x

6 Conclusions

In general, the following conclusions are drawn:

- For the two foundation systems, the bigger the foundation depth, the higher the system rigidity and the lower the settlement and angular distortion, especially for weak soil conditions

- Any unnecessary increase in the foundation thickness should be avoided because it leads to higher bending moments and more costly design

- For weak soil conditions, an optimal raft system seems to be the most appropriate and economic solution, because it has higher rigidity for smaller optimal thickness and it reduces the differential settlement

- Grid systems cause slightly lower stresses in the soil and their discontinuity at the contact surface may lead to better consolidation behavior, which might attract the designer interest when he deals with highly compressible soils

- On the same soil type, foundation area and thickness, the rigidity of the raft is more than that of the grid by Δk_r = 25 [%]

- Angular distortion for the grid is less than that of the raft by 13 [%] to 25 [%]

- For weak soil, the raft saves about 11 [%] material compared with the grid