Introduction to Spread Footings and Mat Foundations

Course No: G02-008

Credit: 2 PDH

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An Introduction to Spread Footings and Mat Foundations

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Editor

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(The figures, tables and formulas in this publication may at times be a little difficult to read, but they are the best available. **DO NOT PURCHASE THIS PUBLICATION IF THIS LIMITATION IS NOT ACCEPTABLE TO YOU**.)

1. GENERAL. When required footings cover more than half the area beneath a structure, it is often desirable to enlarge and combine the footings to cover the entire area. This type of foundation is called a raft or mat foundation and may be cheaper than individual footings because of reduced forming costs and simpler excavation procedures. A mat foundation also may be used to resist hydrostatic pressures or to bridge over small, soft spots in the soil, provided the mat is adequately reinforced. Although mat foundations are more difficult and more costly to design than individual spread footings, they can be used effectively.

2. ADEQUATE FOUNDATION DEPTH. The foundation should be placed below the frost line because of volume changes that occur during freezing and thawing, and also below a depth where seasonal volume changes occur. The minimum depth below which seasonal volume changes do not occur is usually 4 feet, but it varies with location. If foundation soils consist of swelling clays, the depth may be considerably greater. On sloping ground, the foundation should be placed at a depth such that it will not be affected by erosion.

3. FOOTING DESIGN.

3.1 ALLOWABLE BEARING PRESSURES. In many instances, the allowable bearing pressure will be governed by the allowable settlement. The maximum bearing pressure causing settlement consists of dead load plus normal live load for clays, and dead load plus maximum live loads for sands. Subsoil profiles should be examined carefully to determine soil strata contributing to settlement.

3.2 FOOTINGS ON COHESIVE SOILS.

3.2.1 If most of the settlement is anticipated to occur in strata beneath the footings to a depth equal to the distance between footings, a settlement analysis should be made assuming the footings are independent of each other. Compute settlements for the maximum bearing pressure and for lesser values. An example of such an analysis is shown in Figure 1. If significant settlements can occur in strata below a depth equal to the distance between footings, the settlement analysis should consider all footings to determine the settlement at selected footings. Determine the vertical stresses beneath individual footings from influence charts. The footing size should be selected on the basis of the maximum bearing pressure as a first trial. Depending on the nature of soil conditions, it may or may not be possible to proportion footings to equalize settlements. The possibility of reducing differential settlements by proportioning footing areas can be determined only on the basis of successive settlement analyses. If the differential settlements between footings are excessive, change the layout of the foundation, employ a mat foundation, or use piles.

3.2.2 If foundation soils are nonuniform in a horizontal direction, the settlement analysis should be made for the largest footing, assuming that it will be founded on the most unfavorable soils disclosed by the borings and for the smallest adjacent footing. Structural design is facilitated if results of settlement analyses are presented in charts (Fig. 1) which relate settlement, footing size, bearing pressures, and column loads.

Proper footing sizes can be readily determined from such charts when the allowable settlement is known. After a footing size has been selected, compute the factor of safety with respect to bearing capacity for dead load plus maximum live load condition.

3.3 FOOTINGS ON COHESIONLESS SOILS. The settlement of footings on cohesionless soils is generally small and will take place mostly during construction. For the procedure of proportioning footings on sands to restrict the differential settlement to within tolerable limits for most structures, refer to R.B. Peck, W.E. Hanson and T.H. Thornburn, *Foundation Engineering,* 1974, page 312, John Wiley and Sons, Inc., New York, NY.

3.4 FOUNDATION PRESSURES. Assume a planar distribution of foundation pressure for the structural analysis of a footing. This assumption is generally conservative. For eccentrically loaded footings, the distribution of the bearing pressure should be determined by equating the downward load to the total upward bearing pressure and equating the moments of these forces about the center line in accordance with requirements of static equilibrium. Examples of the bearing pressure distribution beneath footings are shown in Figure 2.

4. MAT FOUNDATIONS.

4.1 STABILITY. The bearing pressure on mat foundations should be selected to provide a factor of safety of at least 2.0 for dead load plus normal live load and 1.5 for dead load plus maximum live load. By lowering the base elevation of the mat, the pressure that can be exerted safely by the building is correspondingly increased, and the net increase in loading is reduced. The bearing pressure should be selected so that the settlement of the mat foundation will be within limits that the structure can safely tolerate as a flexible structure. If settlements beneath the mat foundation are more than the rigidity of the structure will permit, a redistribution of loads takes place that will change the pressure distribution beneath the structure, as subsequently described. The bearing capacity of loose sands, saturated silts, and low-density loess can be altered significantly as a result of saturation, vibrations, or shock. Therefore, the allowable bearing pressure and settlement of these soils cannot be determined in the usual manner for the foundation soils may be subject to such effects. Replace or stabilize such foundation soils, if these effects are anticipated.

4.2 CONVENTIONAL ANALYSIS. Where the differential settlement between columns will be small, design the mat as reinforced concrete flat slab assuming planar soil pressure distribution. The method is generally applicable where columns are more or less equally spaced. For analysis, the mat is divided into mutually perpendicular strips.

4.3 APPROXIMATE PLATE ANALYSIS. When the column loads differ appreciably or the columns are irregularly spaced, the conventional method of analysis becomes seriously in error. For these cases, use an analysis based on the theory for beams or plates on elastic foundations. Determine the subgrade modulus by the use of plate load tests. The method is suitable, particularly for mats on coarse-grained soils where rigidity increases with depth.

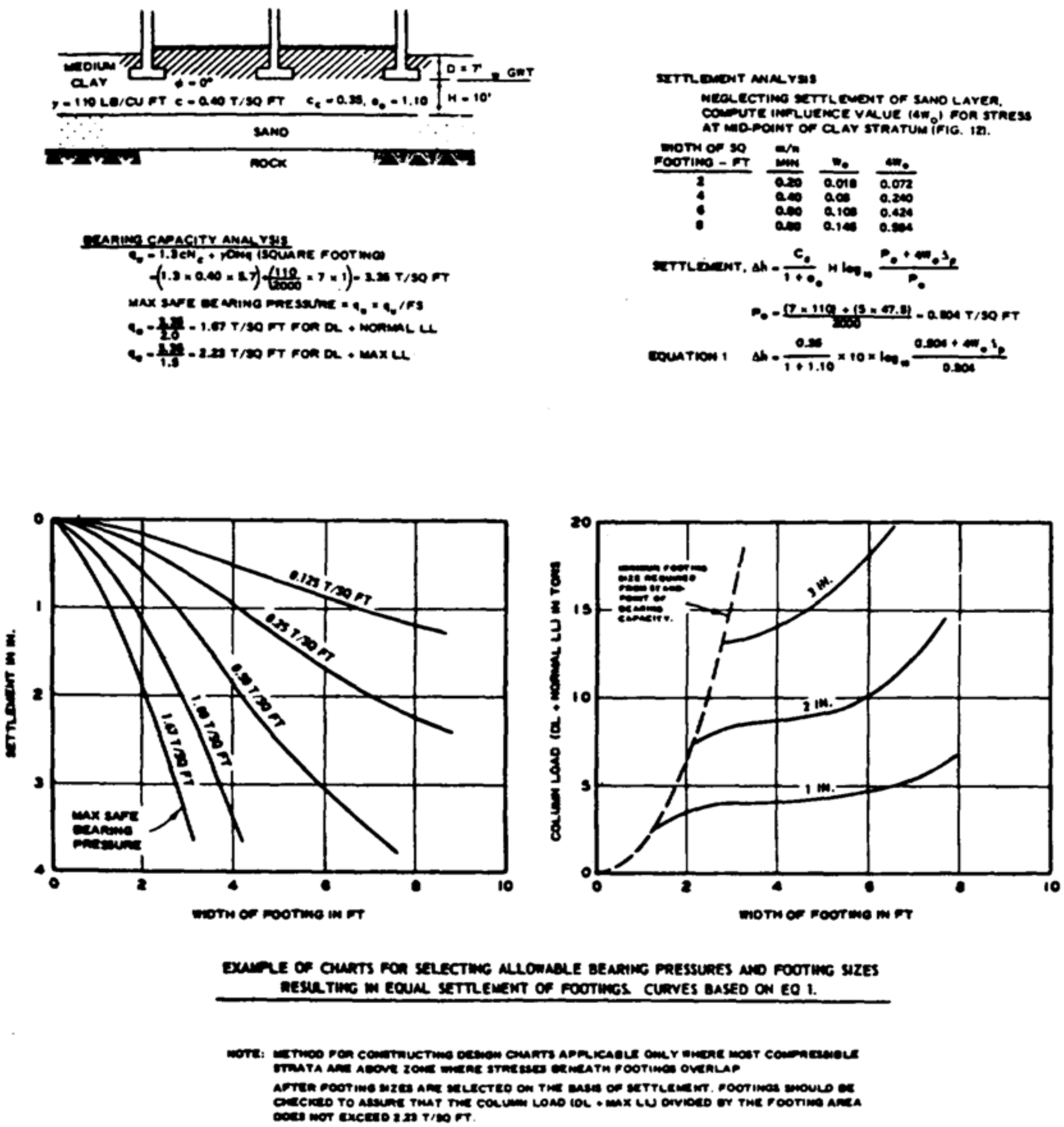

Figure 1

Example of method for selecting allowable bearing pressure

4.4 ANALYSIS OF MATS ON COMPRESSIBLE SOILS. If the mat is founded on compressible soils, determination of the distribution of the foundation pressures beneath the mat is complex. The distribution of foundation pressures varies with time and depends on the construction sequence and procedure, elastic and plastic deformation properties of the foundation concrete, and

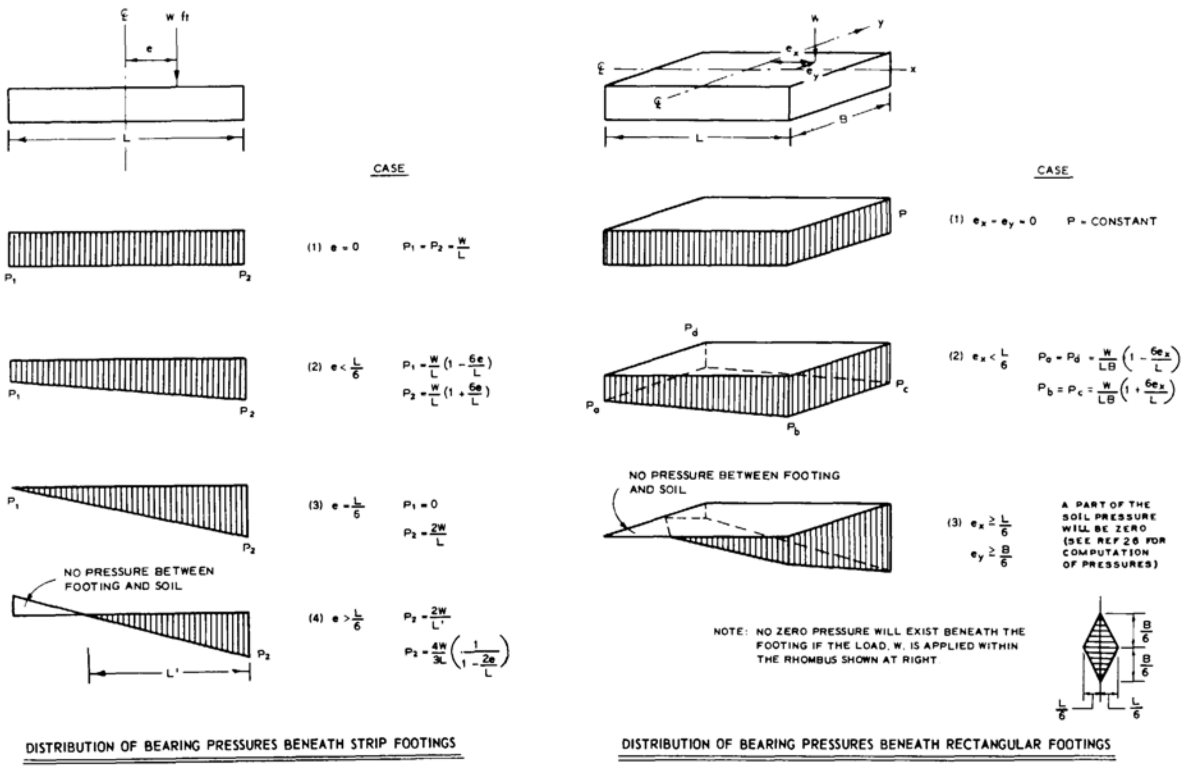

Figure 3

Distribution of bearing pressures

time-settlement characteristics of foundation soils. As a conservative approach, mats founded on compressible soils should be designed for two limiting conditions: assuming a uniform distribution of soil pressure, and assuming a pressure that varies linearly from a minimum of zero at the middle to twice the uniform pressure at the edge. The mat should be designed structurally for whichever distribution leads to the more severe conditions.

5. SPECIAL REQUIREMENTS FOR MAT FOUNDATIONS.

5.1 CONTROL OF GROUNDWATER. Exclude groundwater from the excavation by means of cutoffs, and provide for temporary or permanent pressure relief and dewatering by deep wells or wellpoints. Specify piezometers to measure drawdown levels during construction. Specify the pumping capacity to achieve required drawdown during various stages of construction, including removal of the temporary system at the completion of construction. Consider effects of drawdown on adjoining structures.

5.2 DOWNDRAG. Placement of backfill against basement walls or deep raft foundations constructed in open excavations results in downdrag forces if weight of backfill is significant with respect to structural loading. Estimate the downdrag force on the basis of data published in the technical literature.

6. MODULUS OF SUBGRADE REACTION FOR FOOTINGS AND MATS.

6.1 THE MODULUS OF SUBGRADE REACTION can be determined from a plate load test using a 1- by 1- foot plate.

$$k_{sf} = k_{sl}\ B \qquad \text{(Eq. 1)}$$

where:

k_{sf} = the modulus of subgrade reaction for the prototype footing of width B

k_{sl} = the value of the 1- by 1-foot plate in the plate load test

The equation above is valid for clays and assumes no increase in the modulus with depth, which is incorrect, and may give k_1, which is too large. For footings or mats on sand:

$$k_{sf} = k_{sl}\ [(B + 1)/2B]^2 \qquad \text{(Eq. 2)}$$

For a rectangular footing or mat of dimensions of B x mB:

$$(15m5) \qquad \text{(Eq. 3)}$$

with a limiting value of $k_{sf} = 0.667k_{sl}$

6.2 k_s may be computed as:

$$k_s = 36q_a \text{ (kips per square foot)} \qquad \text{(Eq. 4)}$$

which has been found to give values about as reliable as any method. This equation assumes q_a (kips per square foot) for a settlement of about 1 inch with a safety factor, F = 3.

7. FOUNDATIONS FOR TOWERS.

7.1 GENERAL. This design procedure provides minimum footing dimensions complying with criteria for tilting rotations resulting from operational wind loads. Design of the footing for static load and survival wind load conditions will comply with accepted technical criteria and procedures.

7.2 DESIGN PROCEDURE This design procedure is based upon an effective modulus of elasticity of the foundation. The effective modulus of elasticity is determined by field plate load tests as described below. The design procedure also requires seismic tests to determine the S-wave velocity in a zone beneath the footing at least 1-½ times the size footing required. Field tests on existing radar towers have shown that the foundation performs nearly elastically when movements are small. The required size of either a square or a round footing to resist a specific angle of tilt, a, is determined by the following:

$$B^3 = 4320(F)\ (M/\alpha)\ ([1 - M^2]/E_s)\ \text{(square footing)} \qquad \text{(Eq. 5)}$$

$$D^3 = 6034(F)\ (M/\alpha)\ ([1 - M^2]/E_s)\ \text{(round footing)} \qquad \text{(Eq. 6)}$$

where:

B, D = size and diameter of footing, respectively, feet

F = factor of safety (generally use 2.0)

M = applied moment at base of footing about axis of rotation, foot-pounds

α = allowable angle of tilt about axis of rotation, angular mils (1 angular mil = 0.001 radian)

E_s = effective modulus of elasticity of foundation soil, pounds per cubic foot

The design using equations (5) and (6) is only valid if the seismic wave velocity increases with depth. If the velocity measurements decrease with depth, special foundation design criteria will be required. The discussion of these criteria is beyond the scope of this publication.

7.3 EFFECTIVE MODULUS OF ELASTICITY OF FOUNDATION SOIL (E_S).

Experience has shown that the design modulus of elasticity of in-place soil ranges from 1000 to 5000 kips per square foot. Values less than 1000 kips per square foot will ordinarily present severe settlement problems and are not satisfactory sites for towers. Values in excess of 5000 kips per square foot may be encountered in dense gravel or rock, but such values are not used in design.

7.3.1 Use equations (5) and (6) to compute:

7.3.1.1 Minimum and maximum footing sizes using E_s = 1000 and 5000 kips per square foot, respectively.

7.3.1.2 Two intermediate footing sizes using values intermediate between 1000 and 5000 kips per square foot.

Use these four values of B or D in the following equations to compute the increase (or pressure change) in the live load, ΔL:

square footing: $\Delta L = 17.0M/B^3$ (pounds per square foot) (Eq. 7)

round footing: $\Delta L = 20.3M/D^3$ (pounds per square foot) (Eq. 8)

7.3.2 The E_s value depends on the depth of the footing below grade, the average dead load pressure on the soil, and the maximum pressure change in the live load, ΔL, on the foundation due to wind moments. A determination of the E value will be made at the proposed footing depth for each footing size computed.

7.3.3 The dead load pressure, q_0, is computed as the weight, W, of the tower, appurtenances, and the footing divided by the footing area, A.

$$Q_0 = \Sigma W/A \qquad \text{(Eq. 9)}$$

The selection of loadings for the field plate load test will be based on q_o and ΔL.

7.3.4 FIELD PLATE LOAD TEST PROCEDURE. The following plate load test will be performed at the elevation of the bottom of the footing, with the appropriate test apparatus.

7.3.4.1 Apply a unit loading to the plate equal to the smallest unit load due to the dead load pressure q_0. This unit loading will represent the largest size footing selected above.

7.3.4.2 Allow essentially full consolidation under the dead load pressure increment. Deformation readings will be taken intermittently during and at the end of the consolidation period.

7.3.4.3 After consolidation under the dead load pressure, perform repetitive load test using the live load pressure ΔL computed by the appropriate formulas. The repetitive loading will consist of the dead load pressure, with the live load increment applied for 1 minute. Then release the live load increment and allow to rebound at the dead pressure for 1 minute. This procedure constitutes one cycle of live load pressure application. Deformation readings will be taken at three points: at the start, after the live load is applied for 1 minute, and after the plate rebounds under the dead load pressure for 1 minute. Live load applications will be repeated for 15 cycles.

7.3.4.4 Increase the dead load pressure, q_0, to the second lowest value, allow to consolidate, and then apply the respective live load increment repetitively for 15 cycles.

7.3.4.5 Repeat step 4 for the remaining two dead load pressure increments.

7.3.4.6 An uncorrected modulus of elasticity value is computed for each increment of dead and live load pressure as follows:

$$E_s' = (25.5)\ (\Delta L/S)\ (1 - m^2)$$

where:

E_s' = uncorrected effective modulus of elasticity for the loading condition used, pounds per square foot

S = average edge deformation of the plate for the applied load, determined from the slope of the last five rebound increments in the repetitive load test, inches

m = Poisson's ratio

7.3.4.7 The above-computed uncorrected modulus of elasticity will be corrected for bending of the plate, where E' is defined above, and E, is the effective modulus of elasticity for the test conditions.

7.3.5 SELECTION OF REQUIRED FOOTING SIZE. The required footing size to meet the allowable rotation criteria will be determined as follows:

7.3.5.1 Plot on log-log paper the minimum and the maximum footing size and the two intermediate footing sizes versus the required (four assumed values) effective modulus of elasticity for each footing size.

7.3.5.2 Plot the measured effective modulus of elasticity versus the footing size corresponding to the loading condition used for each test on the same chart as above.

7.3.5.3 These two plots will intersect. The footing size indicated by their intersection is the minimum footing size that will resist the specified angle of tilt.

8. FOUNDATION SELECTION

8.1 FOUNDATION - SELECTION CONSIDERATIONS. Selection of an appropriate foundation depends upon the structure function, soil and groundwater conditions, construction schedules, construction economy, value of basement area, and other factors. On the basis of preliminary information concerning the purpose of the structure, foundation loads, and subsurface soil conditions, evaluate alternative types of foundations for the bearing capacity and total and differential settlements. For some foundation alternatives for different subsoil conditions, refer to L. J. Goodman and R. H. Karol, Theory and Practice of Foundation Engineering, 1968, p 312, Macmillan Company, Inc New York, NY.

8.1.1 SOME FOUNDATION ALTERNATIVES may not be initially obvious. For example, preliminary plans may not provide for a basement, but when cost studies show that a basement permits a floating foundation that reduces consolidation settlements at little or no increase in construction cost, or even at a cost reduction, the value of a basement may be substantial. Benefits of basement areas include needed garage space, office or storage space, and space for air conditioning and other equipment. The last item otherwise may require valuable building space or disfigure a roofline.

8.1.2 WHILE MAT FOUNDATIONS are more expensive to design than individual spread footings, they usually result in considerable cost reduction, provided the total area of spread footings is a large percentage of the basement area. Mat foundations may decrease the required excavation area, compared with spread footings.

8.1.3 THE MOST PROMISING FOUNDATION TYPES should be designed, in a preliminary manner, for detailed cost comparisons. Carry these designs far enough to determine the approximate size of footings, length and number of piles required, etc.

Estimate the magnitude of differential and total foundation movements and the effect on structure. The behavior of similar foundation types in the area should be ascertained.

8.1.4 FINAL FOUNDATION DESIGN should not be started until alternative types have been evaluated. Also, the effect of subsurface conditions (bearing capacity and settlement) on each alternative should be at least qualitatively evaluated.

8.1.5 A CHECKLIST OF FACTORS that could influence foundation selection for family housing is shown in Table 2.

Site Characteristics		Foundations[a]			
Natural Ground	Grading	Post	Spread	Slab-on-Grade (all)	Basement
Level	None	--	--	--	1, 2, 3, 4, 5
Rolling	None	--	--	Requires grading	1, 2, 3, 4, 5
Rolling	Cut and fill	--	1, 2, 3, 4, 5	1, 2, 3, 4, 5	1, 2, 3, 4, 5
Hilly	None	--	--	Requires grading	1, 2, 3, 4, 5
Hilly	Cut and fill	--	1, 2, 3, 4, 5	1, 2, 3, 4, 5	1, 2, 3, 4, 5
Groundwater					
Surface		--	Requires temporary lowering	--	Do not use
Footing level below footing level		--	--	--	Use perimeter drainage
Soil Type					
GW, GP, GM, GC SW, SP, SM, SC		1, 2	1, 2	1, 2	1, 2
ML, CL, OL MH, CH, OH		3, 4, 5, 6	3, 4, 5, 6	3, 4, 5, 6	3, 4, 5, 6

[a] 1. Compaction control - increase density if required, use compaction control in fills.
2. Check relative density of cohesionless (GW, GP, SW, SP) soils; generally based on standard penetration resistance.
3. Use undrained shear strength, s_u , to estimate bearing capacity and stress ratios for slab design.
4. Check if settlement is a problem.
5. Check liquidity index as indication of normally or preconsolidated clay.
6. Check expansive properties.

Table 2

Checklist for Influence of Site Characteristics on Foundation Selection for Residential Housing

8.2 ADVERSE SUBSURFACE CONDITIONS. If poor soil conditions are encountered, procedures that may be used to ensure satisfactory foundation performance include the following:

8.2.1 BYPASS THE POOR SOIL by means of deep foundations extending to or into a suitable bearing material.

8.2.2 DESIGN THE STRUCTURE FOUNDATIONS to accommodate expected differential settlements. Distinguish between settlements during construction that affect a structure and those that occur during construction before a structure is affected by differential settlements.

8.2.3 REMOVE THE POOR MATERIAL, and either treat and replace it or substitute good compacted fill material.

8.2.4 TREAT THE SOIL IN PLACE prior to construction to improve its properties. This procedure generally requires considerable time. The latter two procedures are carried out using various techniques of soil stabilization.

8.3 COST ESTIMATES AND FINAL SELECTION.

8.3.1 ON THE BASIS OF TENTATIVE DESIGNS, the cost of each promising alternative should be estimated. Estimate sheets should show orderly entries of items, dimensions, quantities, unit material and labor costs, and cost extensions. Use local labor and material costs.

8.3.2 THE PRELIMINARY FOUNDATION DESIGNS that are compared must be sufficiently completed to include all relevant aspects. For example, the increased cost of piling may be partially offset by pile caps that are smaller and less costly than spread footings. Similarly, mat or pile foundations may require less excavation. Foundation dewatering during construction may be a large item that is significantly different for some foundation alternatives.

8.3.3 THE MOST APPROPRIATE TYPE OF FOUNDATION generally represents a compromise between performance, construction cost, design cost, and time. Of these, design cost is generally the least important and should not be permitted to be a controlling factor. If a lower construction cost can be achieved by an alternative that is more expensive to design, construction cost should generally govern.

8.3.4 FOUNDATION SOILS PRETREATMENT by precompression under temporary surcharge fill, regardless of whether vertical sand drains are provided to accelerate consolidation, requires a surcharge loading period of about 6 months to a year. The time required may not be available unless early planning studies recognized the possible foundation cost reduction that may be achieved. Precompression is frequently advantageous for warehouses and one-story structures. Precompression design should be covered as a separate design feature and not considered inherent in structure design.