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Study of Low-Cost Foundation/Anchor Designs for Single-Axis-Tracking Solar Collector Systems

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STUDY OF LOW COST FOUNDATION/ANCHOR DESIGNS FOR SINGLE-AXIS-TRACKING SOLAR COLLECTOR SYSTEMS

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ABSTRACT

The requirements for the foundations of single-axis-tracking solar collector systems are defined. Ten preliminary foundation systems capable of meeting these requirements are evaluated in relation to deployability and cost-effectiveness. A detailed design is presented for the optimal system and two alternative designs.

CONTENTS

SECTION I
INTRODUCTION

1. BACKGROUND

The Federal Government is committed to developing alternative sources of energy such as solar, geothermal, tidal and wind. Solar energy is receiving a great deal of interest, and the United States Department of Energy (DOE) has funded Sandia Laboratories to field prototype solar-conversion systems for demonstration and evaluation. One of the more promising systems utilizes single-axis-tracking solar collector arrays. A typical application for such arrays is to provide the power for pumping irrigation water for agricultural projects in the Southwest. Figure 1 is an artist's conception of the DOE solar-irrigation project in the Estancia Valley, near Albuquerque, New Mexico.

Existing single-axis-tracking solar collector systems are supported by rows of pedestals which rest on cylindrical pier foundations of reinforced concrete. The foundation designs which have been utilized are relatively expensive and contribute a significant percentage to the overall cost of the collector field. Every component of the system must be designed to meet minimum cost objectives if solar energy is to become a cost-competitive alternative source of energy. Therefore, it is necessary to evaluate the foundation requirements for this system and to insure that cost-effective foundation designs are available for future installations.

2. OBJECTIVE

The objective of this study is to develop minimum-cost foundation designs for a typical single-axis-tracking solar collector system which may be sited anywhere in the southwest portion of the United States. To meet this objective, the following approach was utilized:

a. Comprehensive criteria for the foundation designs were defined. These criteria consisted of foundation loads, performance requirements, and geotechnical parameters.

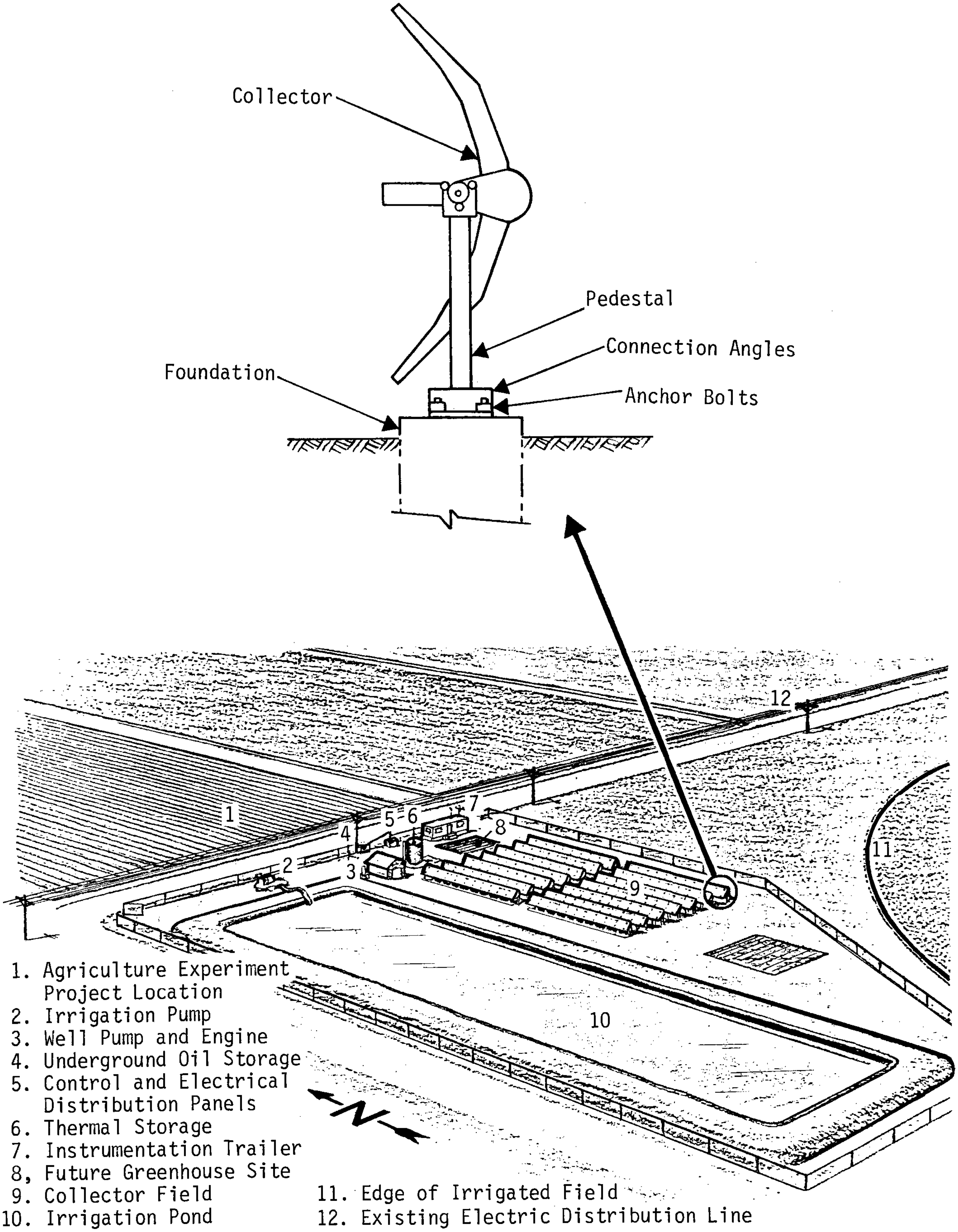

Figure 1. Artist's Concept of DOE Solar Pumping Project in Estancia Valley, New Mexico

b. Ten concepts of the potential foundations were developed, and their preliminary design was completed to the extent that cost estimates could be prepared and the concepts could be judged against the design criteria.

c. Detailed designs were completed for the three most promising foundation concepts. Emphasis was placed on compatibility with standard construction practices to insure that costs for the foundation could be kept to a minimum.

SECTION II
FOUNDATION DESIGN CRITERIA

1. APPLIED LOADS

Based on the approach contained in Sandia Laboratories' Memo*, the following assumptions were made in order to calculate wind loads:

a. A 100-year wind of 90 mph at 30 ft above ground governed the design.

b. Maximum wind could be corrected from 30 ft to 5 ft using 1/7 power rule.

c. Altitude corrections were not appropriate, since systems may be sited anywhere.

d. Shielding allowances were not appropriate at this time. Shielding allowances should be included in future studies, if wind tunnel tests now underway confirm the significance of this phenomenon.

e. Collectors had a 6-ft aperture and were constructed in 20-ft-long modules.

The aerodynamic drag (D) or lift (L) can be computed from

$$D \text{ or } L = 1/2\ \rho V^2\ (C_D \text{ or } C_L)S \tag{1}$$

where

ρ = 0.002378 lb s^2/ft^4 at sea level

V = wind velocity, ft/s

S = surface area = 120 ft^2

C_D or C_L = drag or lift coefficient (see Table 1)

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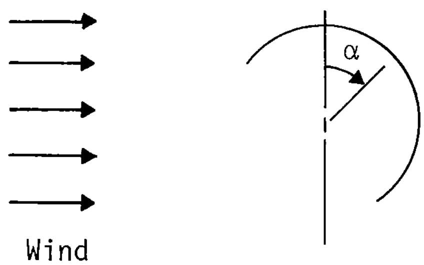
*Thunborg, S., "Minutes of Foundation and Structure Loads Meeting," Sandia Laboratories, Albuquerque, New Mexico, 11 July 1978.

Based on References 1 and 2, aerodynamic lift and drag coefficients were estimated and are presented in Table 1.

TABLE 1. AERODYNAMIC LIFT AND DRAG COEFFICIENTS FOR SOLAR COLLECTORS



α = angle of rotation

α, DEGREE	0	10-20	90	180	270	340-350
C_L	1.2	2.0	0.0	-1.2	0.0	-2.0
C_D	0.6	0.5	2.0	0.6	1.0	0.5

Correcting for height using

$$V = V_{ref} \left(\frac{h}{h_{ref}}\right)^{\frac{1}{7}} \tag{2}$$

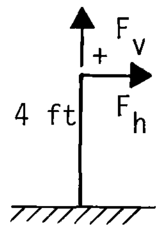
$$= 90 \text{ mph} \left(\frac{5 \text{ ft}}{30 \text{ ft}}\right)^{\frac{1}{7}} = 69.7 \text{ mph}$$

and assuming the weight of the collector on each pedestal to be 500 lb, the system of forces given in Table 2 result.

1. Kinney, G.F., ed., *Explosive Shocks in Air*, The Macmillan Company, New York, 1962.

2. Marks, L.S., ed., *Mechanical Engineer's Handbook*, McGraw Hill Book Company, Inc., New York, 1951.

TABLE 2. FOUNDATION LOADS FOR VARIOUS COLLECTOR ORIENTATIONS



Note: F_v = vertical foundation load
F_h = horizontal foundation load

α, DEGREES*	0	10-20	90	180	270	340-350
F_v, lb	1300	2500	0	-2300	-500	-3500
F_h, lb	900	850	3000	900	1500	750

*See Table 1.

Under normal operating conditions α should vary between 90 and 270 deg. An angle of inclination, α, of 0 or 10-20 deg represents a stowed or nearly stowed configuration, which is appropriate for maximum wind conditions. Therefore, a factor of safety ≥ 3 against uplift or a failure of the rotational bearing capacity should be provided for either of these loading conditions. It is extremely unlikely that an orientation of α = 90 deg would occur under maximum wind conditions and a factor of safety ≥ 1 should be adequate. A factor of safety ≥ 2 is appropriate for the remaining orientations.

2. PERFORMANCE REQUIREMENTS

Each preliminary foundation concept will be evaluated against the following performance requirements to judge its relative merit:

a. Ability to support applied foundation loads with desired factors of safety as outlined in Section II-1.

b. Constructability; e.g., some systems may not be constructable at sites where the subsurface material is extremely competent or contains large gravel or boulders.

c. Accuracy of location; anchor bolts for collector pedestals should be located to the following field tolerances:

lateral - ±1/4 in

vertical - ±1/4 in

Tolerances of these magnitudes have recently been obtained for the foundations of a single-axis-tracking solar collector project under construction in Arizona, where the contractor utilized specially-built jigs. It is felt that similar results can be achieved in future projects if sufficient emphasis is placed on the tolerance requirements at pre-bid construction conferences.

d. Permanent displacement under maximum loading conditions:
   ± 0.1 in either vertically or horizontally

e. Miscellaneous:
   - familiarity of contractors with construction technique.
   - interference with collector-array operation.
   - location of base of the foundation below the frost line.

In addition to these requirements, the foundation costs should be kept to a minimum. It may not be possible to utilize the least expensive concept under all field conditions, and alternate concepts will therefore be developed.

3. GEOTECHNICAL PARAMETERS

This study considered two types of site conditions which were labeled *typical* and *poor*. Actual parameters were estimated for a majority of the sites where single-axis-tracking solar collector systems may be located within the southwest portion of the United States. Geotechnical parameters at a *typical* site were defined such that they form a lower bound to these actual parameters. Geotechnical parameters at a *poor* site were defined as the worst conditions for which construction should be considered. On the basis of its general behavior characteristics, soil at both *typical* and *poor* sites can generally be categorized as either granular or cohesive. In some instances, it may exhibit some of both characteristics.

A *typical granular soil* is described as medium-dense sandy gravel and gravelly sand or medium-dense to dense well-graded sand. It will have an angle of internal friction, ϕ, of $\geq$ 40 deg and will have a standard penetration resistance, N, of $\geq$ 45 blows/ft.

A *typical cohesive soil* is described as a stiff to very stiff clay or silty clay. It will have a cohesive shear strength, C, of $\geq$ 2000 lb/ft^2.

A *poor granular soil* is described as loose, fine to medium sand, e.g., an uncompacted sandfill. It will have an angle of internal friction, ϕ, of between 30 and 40 deg and will have a standard penetration resistance, N, of between 5 and 45 blows/ft.

A *poor cohesive soil* is described as soft to medium clay or silty clay. It will have a cohesive shear strength, C, of between 500 and 2000 lb/ft^2.

When actual construction sites are selected, an experienced geotechnical engineer should visit the site to determine the appropriate geotechnical parameters. Since all of the foundation concepts are fairly shallow, a literature review plus a few simple field tests should be sufficient for most circumstances. In addition, the geotechnical engineer should provide information with regard to the constructability of the various foundation concepts and should recommend which of the concepts he deems most appropriate.

SECTION III

DEVELOPMENT AND EVALUATION OF FOUNDATION CONCEPTS

1. INTRODUCTION

The ten foundation concepts initially considered in this study were:

a. Cylindrical reinforced concrete pier

b. Steel pipe column

c. Rectangular concrete footing

d. Rectangular reinforced concrete pier

e. Bent

f. Reinforced concrete mat

g. Steel beam with tiedowns

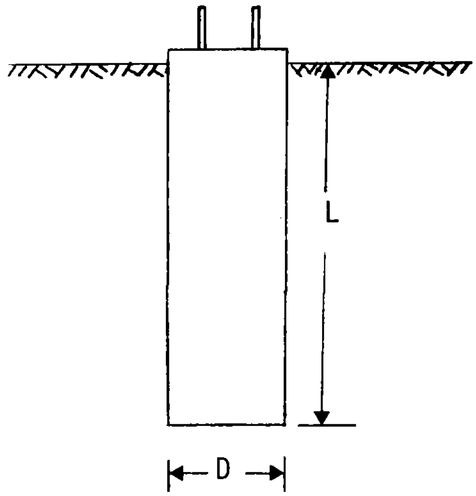
h. Reinforced concrete pad with tiedowns

i. Earth anchor with tiedowns

j. Earth anchors

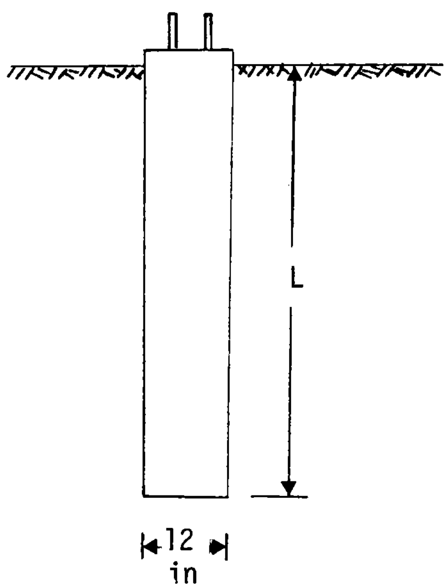
The preliminary designs for these concepts are summarized in Figures 2a through 2e. Cost estimates for these preliminary designs are presented in Appendix A and the results are summarized in Table 3. The following subsections present design considerations and a brief discussion of each concept with an evaluation of the design against the performance requirements given in Section II-2.

a. Cylindrical Reinforced Concrete Pier



	Typical Site	*Poor* Site
D, in	16	18
L, ft	5	7-1/2

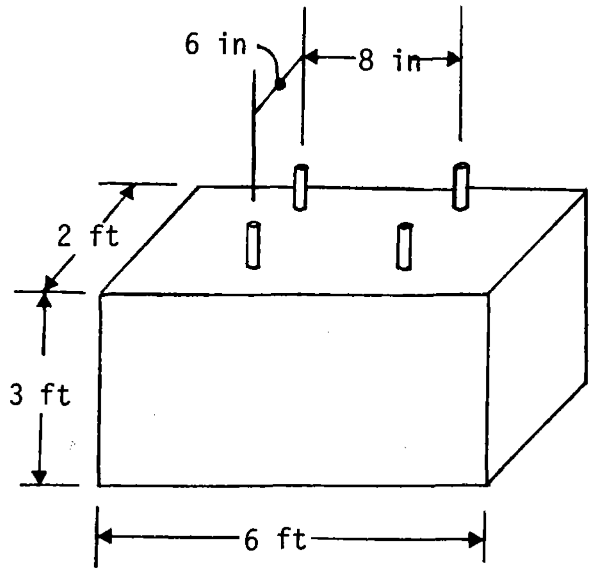
b. Steel Pipe Column



	Typical Site	*Poor* Site
L, ft	6-1/2	12

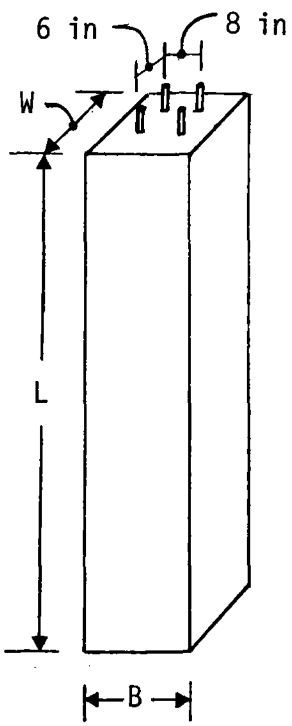
Figure 2a. Preliminary Design Details

c. Rectangular Concrete Footing



Note: Same design is used for both *typical* and *poor* sites.

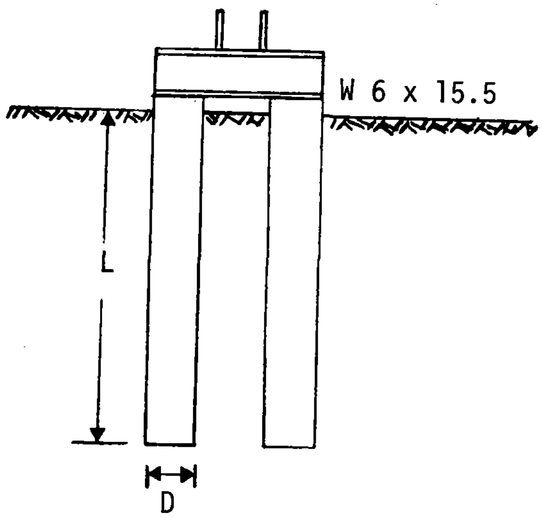
d. Rectangular Reinforced Concrete Pier



	Typical Site	*Poor* Site
W, in	10	12
B, in	15	18
L, ft	5-1/2	7

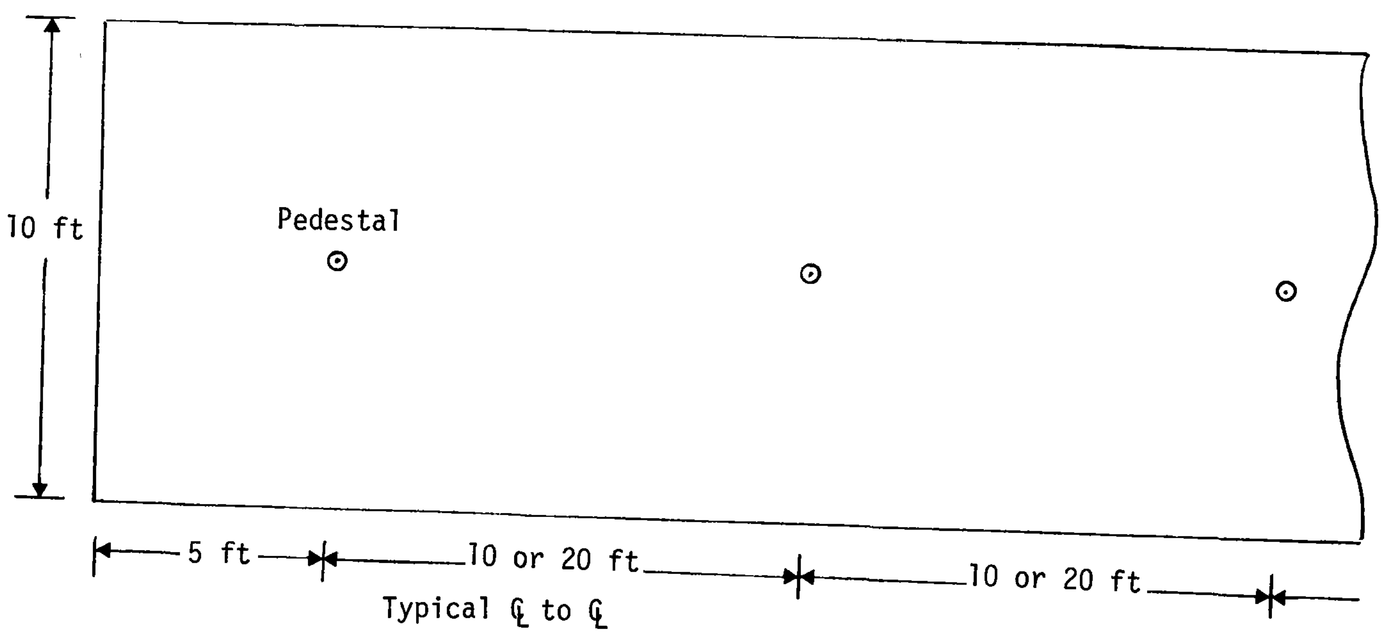
Figure 2b. Preliminary Design Details

e. Bent



	Typical Site	*Poor* Site
D, in	9	18
L, ft	5	7

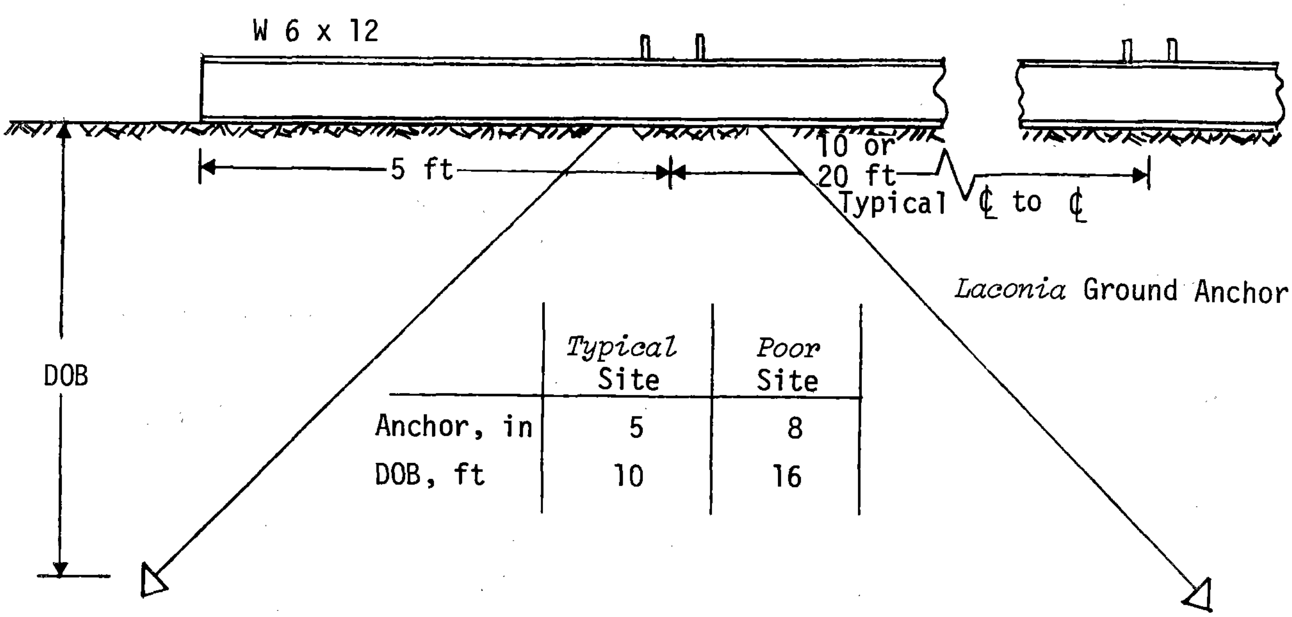
f. Reinforced Concrete Mat



Note: This is a 6-in slab and the same design is used for both *typical* and *poor* sites.

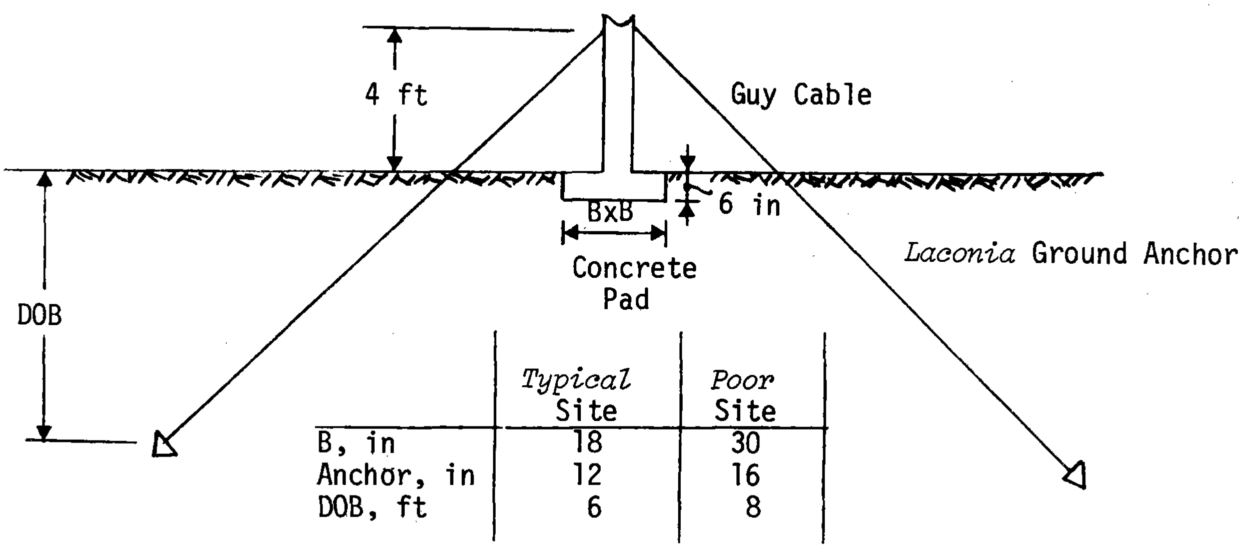
Figure 2c. Preliminary Design Details

g. Steel Beam with Tiedowns



	Typical Site	*Poor* Site
Anchor, in	5	8
DOB, ft	10	16

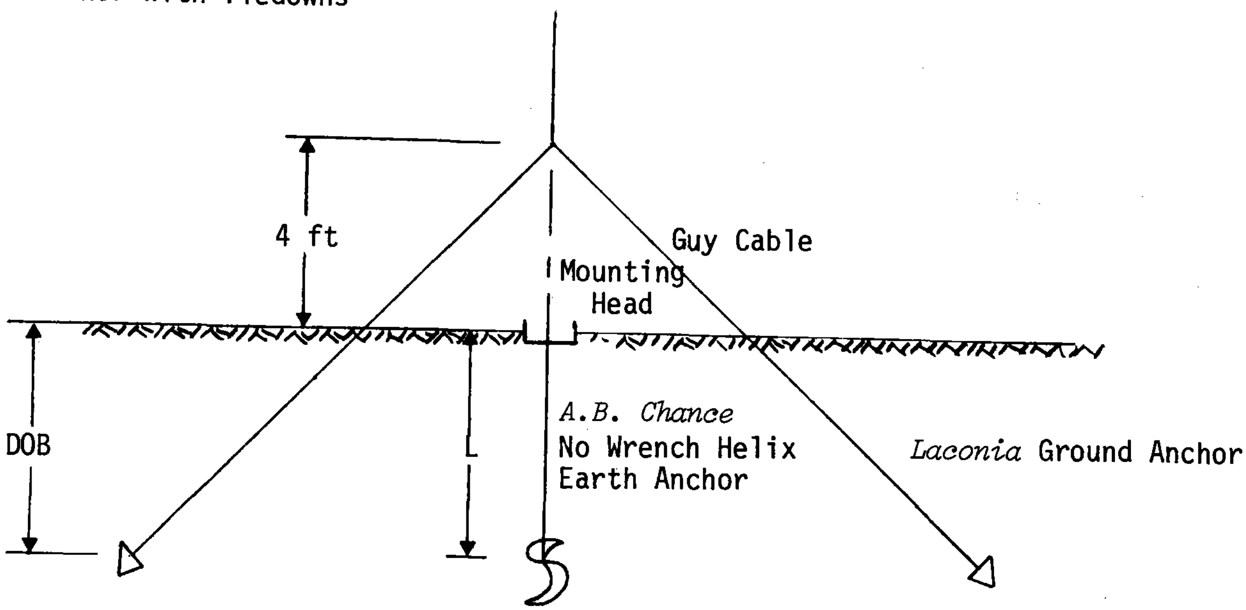
h. Reinforced Concrete Pad with Tiedowns



	Typical Site	*Poor* Site
B, in	18	30
Anchor, in	12	16
DOB, ft	6	8

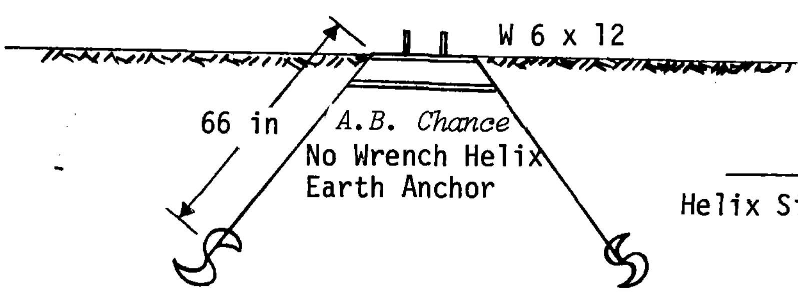
Figure 2d Preliminary Design Details

i. Earth Anchor With Tiedowns



	Typical Site	*Poor* Site
Helix Size, in	4	8
L, in	54	66
Anchor Size, in	10	16
DOB, ft	5	8

j. Earth Anchors



	Typical Site	*Poor* Site
Helix Size, in	6	10

Figure 2e. Preliminary Design Details

TABLE 3. SUMMARY OF COST ESTIMATES FOR PRELIMINARY DESIGNS

Design	Description	\$, *Typical* Site	\$. *Poor* Site
a	Cylindrical reinforced concrete pier	[illegible]8	126
b	Steel pipe column	211	375
c	Rectangular concrete footing	203	203
d	Rectangular reinforced concrete pier	[illegible]3	170
e	Bent	124	279
f	Reinforced concrete mat	245	245
g	Steel beam with tiedowns	154	204
h	Reinforced concrete pad with tiedowns	129	176
i	Earth anchor with tiedowns	173	262
j	Earth anchors	161	225

2. DESIGN CONSIDERATIONS

References 3, 4, 5, 6, and 7 were utilized to accomplish the preliminary design of the bulk of the foundation concepts. However, there was no standard reference available for the design of short rigid piles subjected to inclined loads. Since three of the concepts fell into this category, equations were developed for their design. This development is presented in Appendix B.

Separate designs were accomplished for each of the site categories, *typical* and *poor*. In some instances the same design was appropriate for both categories. The approach utilized was to first consider a site to have the characteristics of a granular material and then to consider it to have the characteristics of a cohesive material. The results presented herein are based on the governing or worst-case condition for each site category.

It was assumed that the water table at all potential sites is located at a sufficient depth such that it will not influence the design results. This depth is generally considered to be equal to or greater than the largest dimension of the foundation system. The effect of more shallow water tables can be treated with standard approaches. (See Ref. 3, for example.)

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3. Peck, R.B., Hanson, W.E., and Thornburn, T.H., *Foundation Engineering*, Second Edition, John Wiley and Sons, Inc., 1974.

4. *Encyclopedia of Anchoring--Principles and Applications of Earth Anchors*, A.B. Chance Company, Centralia, Missouri, 1977.

5. *Now There's An Easy-to-Install Anchor That Really Holds*, Laconia Malleable Iron Company, Laconia, New Hampshire, 1975.

6. Wang, C.K., and Salmon, C.G., *Reinforced Concrete Design*, Second Edition, Intext Educational Publishers, 1973.

7. Oden, J.T., *Mechanics of Elastic Structures*, McGraw-Hill Book Company, 1967.

3. DISCUSSION AND EVALUATION

a. Cylindrical Reinforced Concrete Pier

See Figure 2a for a sketch and dimensions of the concept. As indicated in Table 3, this is the least expensive design for both *typical* and *poor* sites, costing $78 and $126 respectively. It was assumed that a flight auger could be used to advance the hole and that the hole would remain open until after the concrete was placed. All of the performance requirements can normally be met with this design. Since it is the least expensive, it should be utilized whenever possible. The only exception would involve problems of constructability. Extremely competent subsurface material or the presence of large-grained particles (such as large gravel or boulders) could preclude the use of a flight auger to advance the hole to the required depth. In these instances a more costly concept may be required.

b. Steel Pipe Column

See Figure 2a for a sketch and dimensions of the concept. As indicated in Table 3, this is one of the most expensive designs for both *typical* and *poor* sites, costing $211 and $375 respectively. The high cost results from the cost of the galvanized steel pipe column. It was assumed that a backhoe could be used to press the pipe column into the ground to the required depth. A top plate with anchor bolts could then be accurately welded in place in the field. This design satisfies all of the performance requirements except for constructability at sites with extremely competent or coarse-grained subsurface material. However, it has been dropped from further consideration in this study because of its high cost.

c. Rectangular Concrete Footing

See Figure 2b for a sketch and dimensions of the concept. The same design will perform satisfactorily at both *typical* and *poor* sites and is estimated to cost $203 (see Table 3). It was assumed that a backhoe could be used to excavate the rectangular hole to the approximate dimensions and that only minimum forming would be required to bring the concrete to the proper grade. This design satisfies all of the performance requirements and should be constructable at virtually any site. Therefore, in spite of its relatively high cost, it was selected as one of the concepts for further consideration.

d. Rectangular Reinforced Concrete Pier

See Figure 2b for a sketch and dimensions of the concept. As indicated in Table 3, this concept is estimated to cost $93 and $170, respectively, at *typical* and *poor* sites. Although this is a relatively inexpensive design, it offers no advantages over the cylindrical reinforced concrete pier design. It would be extremely difficult to excavate a small rectangular hole accurately to the required depths. Therefore, this concept has been dropped from further consideration in this study.

e. Bent

See Figure 2c for a sketch and dimensions of the concept. It is estimated to cost $124 and $279, respectively, at *typical* and *poor* sites, as indicated in Table 3. It was assumed that a flight auger could be used to advance the holes and that they would remain open until after the concrete was placed. The double-pier arrangement provides more stiffness than a single pier, and the steel section can be utilized to partially correct for location errors. This concept will meet all of the performance requirements except for constructability at sites with extremely competent or coarse-grained subsurface material. This concept will be further developed in the next section.

f. Reinforced Concrete Mat

See Figure 2c for a sketch and dimensions of the concept. The same design will perform satisfactorily at both *typical* and *poor* sites, and is estimated to cost $245 (see Table 3). The reinforced concrete mat offers no advantages over the rectangular concrete footing, is estimated to be more expensive, and may be subject to frost heaves. Therefore, this concept has been dropped from further consideration in this study.

g. Steel Beam with Tiedowns

See Figure 2d for a sketch and dimensions of the concept. It is estimated to cost $154 and $204, respectively, at *typical* and *poor* sites, as indicated in Table 3. A galvanized steel section is assumed to be continuous across several rows of collectors. *Laconia* ground anchors (Ref. 5) are utilized for tiedowns. The site must be relatively uniform to preclude the necessity for large amounts of earth work. The steel section may be prone to long-term corrosion problems and it will be extremely difficult to achieve uniform seating along its entire length. Many contractors will not be familiar with the *Laconia* ground anchor system and some might be reluctant to bid on this concept without increasing their price to compensate for the uncertainties. In addition, these anchors cannot be driven into extremely competent or coarse-grained subsurface materials. Therefore, this concept has been dropped from further consideration in this study.

h. Reinforced Concrete Pad with Tiedowns

See Figure 2d for a sketch and dimensions of the concept. It is estimated to cost $129 and $176, respectively, at *typical* and *poor* sites, as indicated in Table 3. This concept also utilizes *Laconia* ground anchors for tiedowns and the comments made in the previous subsection also apply here. In addition, the guy cable from the tiedowns to the pedestals may interfere with the operation of the collector system. The base of the concrete pads are probably located above the frost line at most sites and large long-term vertical displacements could occur. Therefore, this concept has been dropped from further consideration in this study.

i. Earth Anchor with Tiedowns

See Figure 2e for a sketch and dimensions of the concept. It is estimated to cost $173 to $262, respectively, at *typical* and *poor* sites, as indicated in Table 3. This concept utilizes an *A.B. Chance* helix earth anchor (Ref. 4), oriented vertically, and *Laconia* ground anchors for tiedowns. It was assumed, in estimating costs, that the helix earth anchor could be placed by hand, and therefore, this concept is limited to sites with rather weak subsurface materials. Power-digger and wrench assemblies can be utilized to install heavier earth anchors in more competent materials, but the use of heavy equipment and more expensive materials will drive up the cost estimate considerably. Many contractors will be unfamiliar with the two anchor systems utilized in this concept. In addition, the guy cables from the tiedowns to the pedestals may interfere with the operation of the collector system. Therefore, this concept has been dropped from further consideration in this study.

j. Earth Anchors

See Figure 2e for a sketch and dimensions of the concept. It is estimated to cost \$161 and \$225, respectively, at *typical* and *poor* sites, as indicated in Table 3. This concept utilizes two *A.B. Chance* helix earth anchors, oriented at 45 and 135 deg with a steel section head welded to the top of the drive rods in the field. It was assumed for cost-estimating purposes that the helix earth anchors could be placed by hand and therefore, this concept is limited to sites with rather weak subsurface materials, e.g., a *poor* site. Also, many contractors will be unfamiliar with the *A.B. Chance* earth anchor system. Therefore, this concept has been dropped from further consideration in this study.

SECTION IV

DETAILED DESIGNS

1. GENERAL DISCUSSION

As indicated in the previous section, cylindrical reinforced concrete piers which meet the criteria of Section II are estimated to be the most cost-effective foundation system for use with single-axis-tracking solar collector arrays. This system should be utilized whenever site conditions meet the design assumptions; i.e., a flight auger can be utilized to advance a hole of the proper diameter to the required depth and the hole will remain open without the use of forming until the concrete has been poured. The bent was selected as an alternate design because it had some advantages over the single cylindrical reinforced concrete pier design. However, it was assumed that the same general construction techniques would be utilized, and the concrete pier is not appropriate for sites with extremely competent or large-grained subsurface materials.

In those instances where a pier and/or piers are not appropriate, a rectangular concrete footing can be utilized. It was assumed that a backhoe could be utilized to perform most of the excavation for this footing and that only minimum forming would be required. If these assumptions are not satisfied, the cost estimate will increase accordingl[illegible]

Detailed cost estimates were reaccomplished to [illegible]e three desi[illegible] selected for further development in this section. Suppliers in the Albuquerque area were contacted for cur[illegible] utilizing the assumptions presented in Appendix A. The detailed cost estimates agreed with the values given in Table 3 within ±10 percent and are not repeated.

In the remainder of this section, designs for use at *typical* sites are presented for the reinforced concrete pier and bent concepts. Similar designs can be developed for use at *poor* sites. The rectangular concrete footing design can be used at both *typical* and *poor* sites.

2. CYLINDRICAL REINFORCED CONCRETE PIER

The details of the pier design for a *typical* site are given in Figure 3. It was assumed that no site preparation was required, that a flight auger could advance the 16-in-diameter hole to the appropriate depth, and that the material at the bottom of the hole would not be compacted. A reuseable metal form is utilized to achieve the proper grade and to prevent the sloughing of the near-surface material into the hole.

It was assumed that the reinforced cage and anchor bolts would be prefabricated and placed as a unit. A jig should be used to insure that the anchor bolts are located to the tolerances given in Section II-2. These tolerances should be easily attained by utilizing normal construction practices. Shims can be used to attain the final vertical alignment. The system contractor must provide for final lateral alignment.

3. BENT

The details of the bent design for a *typical* site are given in Figures 4a and 4b. The general features of the piers are the same as those discussed in the previous subsection, with three exceptions: two piers are required for this design, the piers are smaller in diameter, and only two anchor bolts are required to accommodate the structural steel section.

The final lateral alignment of the piers can be achieved with the oversized holes specified in the structural steel section. A 1/4-in x 8-in x 10-in flange and two 1/4-in x 3-in x 3-in stiffener plates must be fillet-welded to the steel section to avoid buckling.

4. RECTANGULAR CONCRETE FOOTING

The details of the footing design are given in Figure 5. This design can be utilized at any site where a collector array could be considered for construction, i.e., a *typical* or a *poor* site. It was assumed that no

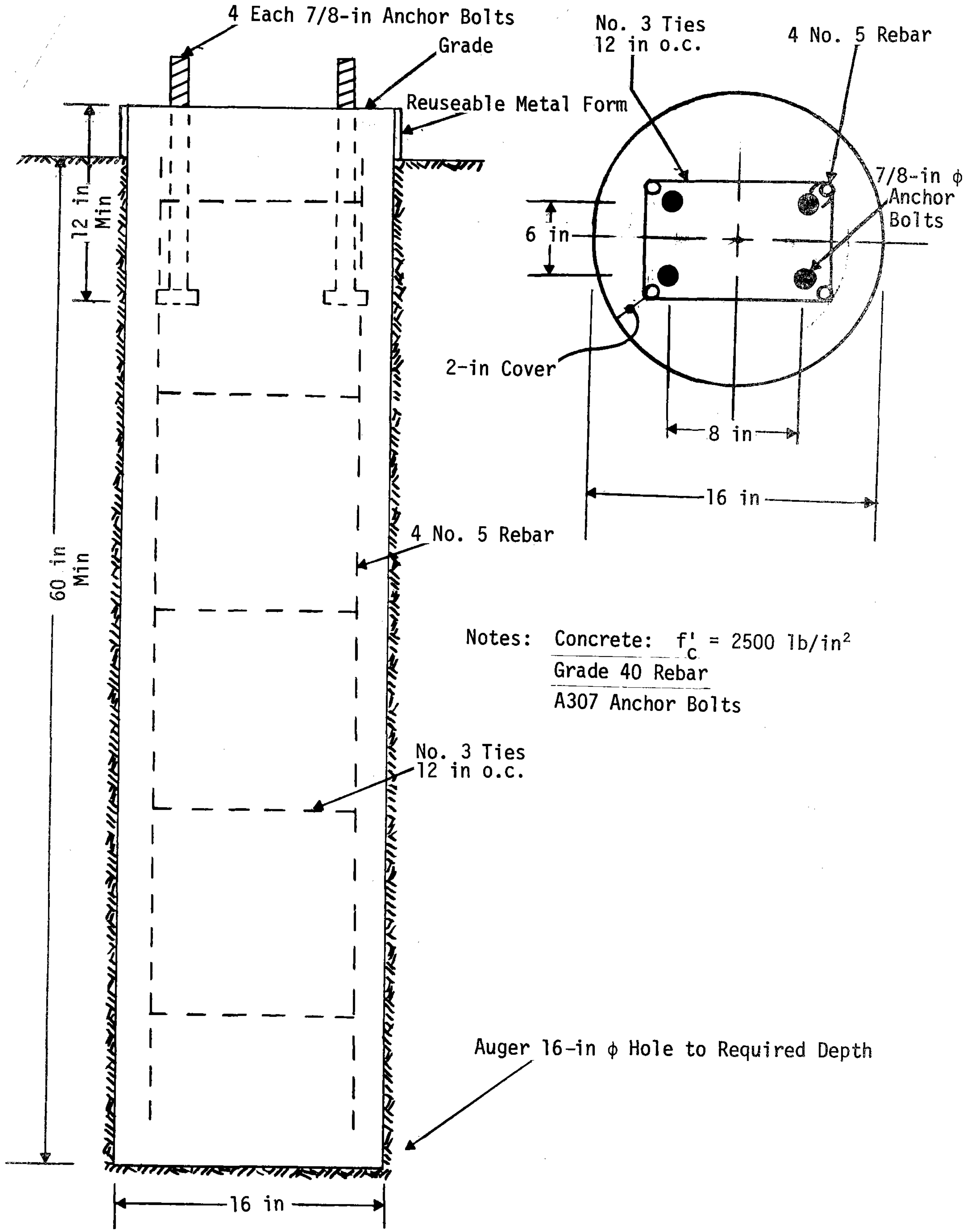


Figure 3. Detailed Pier Design, *Typical* Site

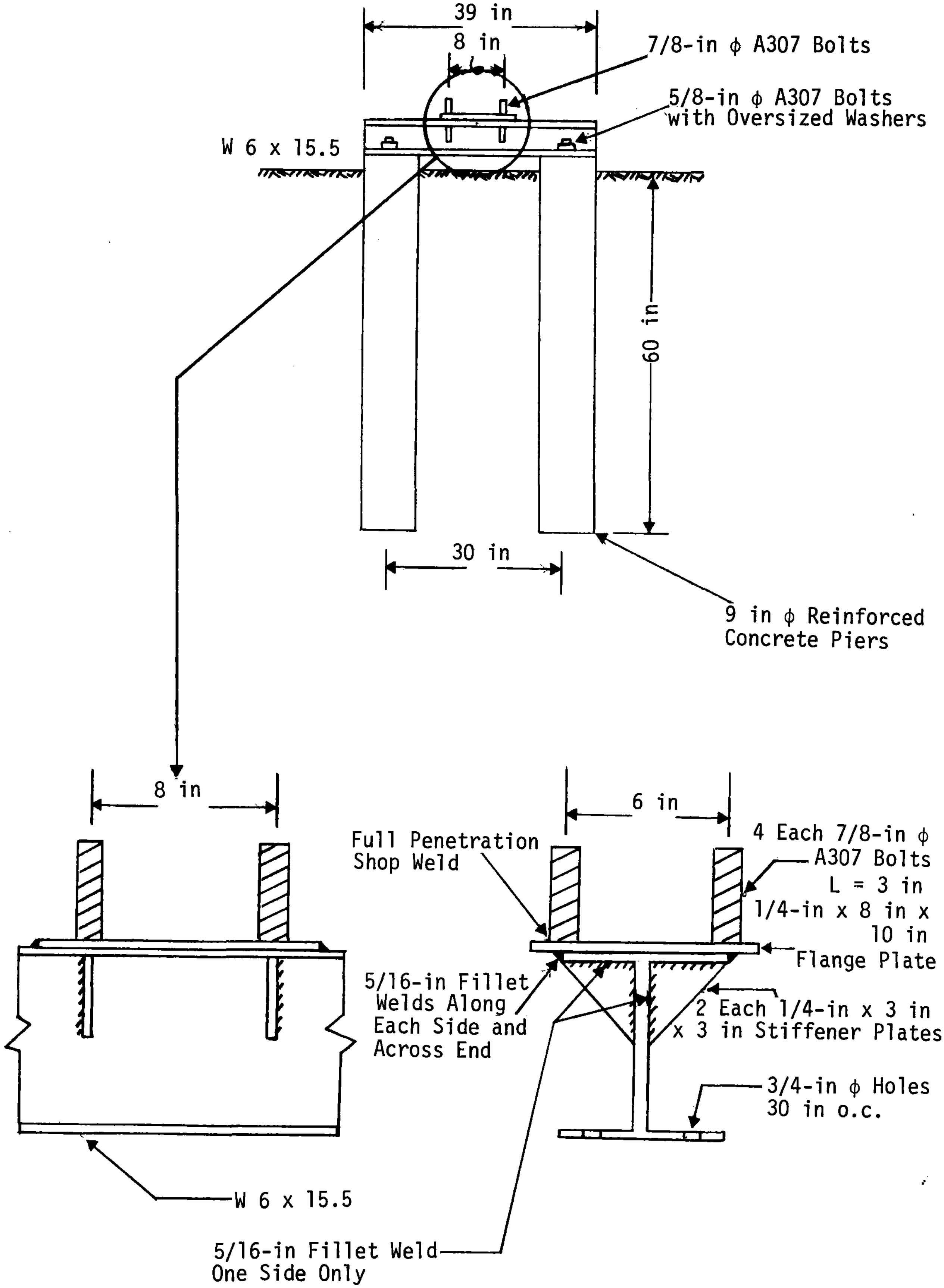


Figure 4a. Detailed Bent Design, *Typical* Site

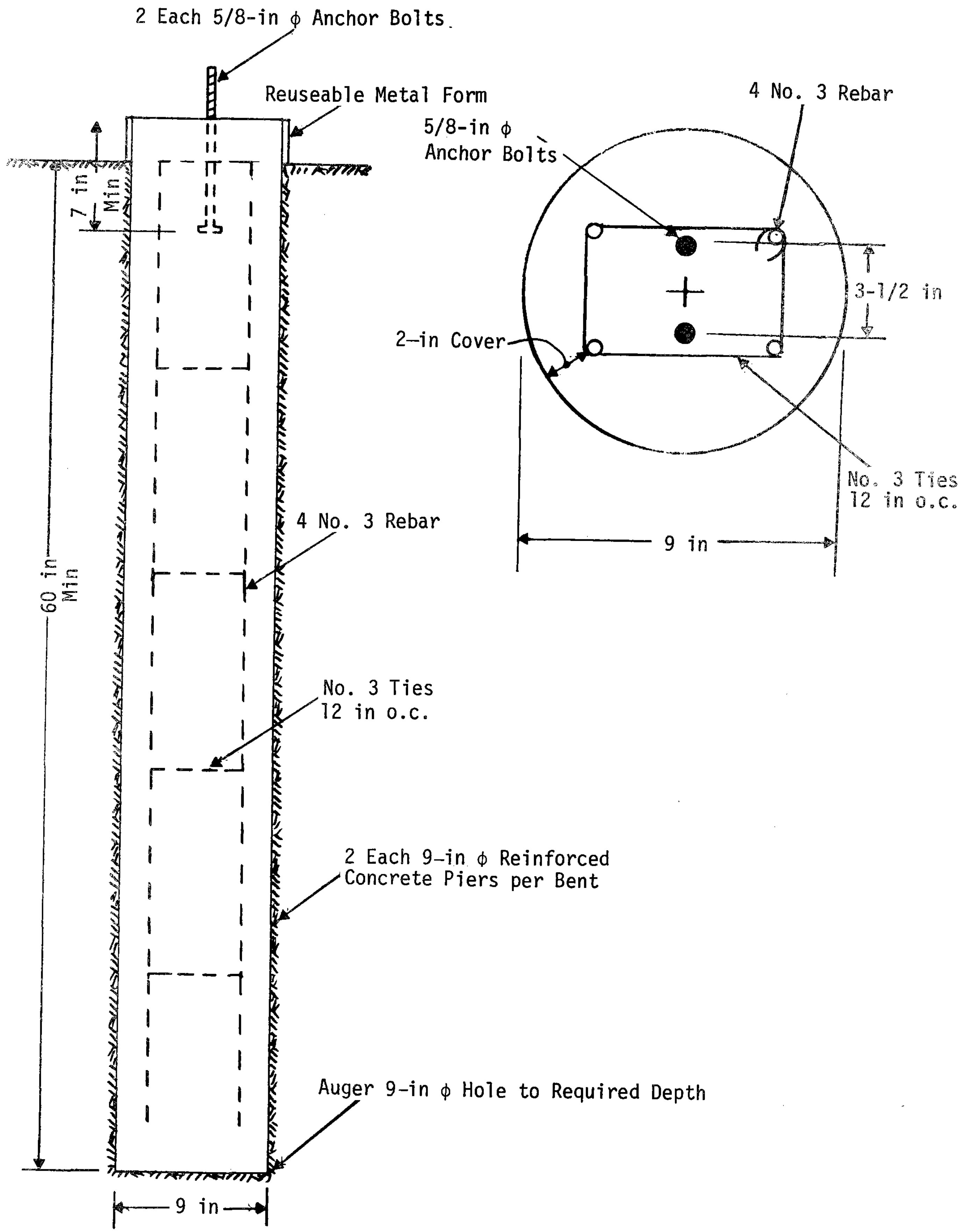
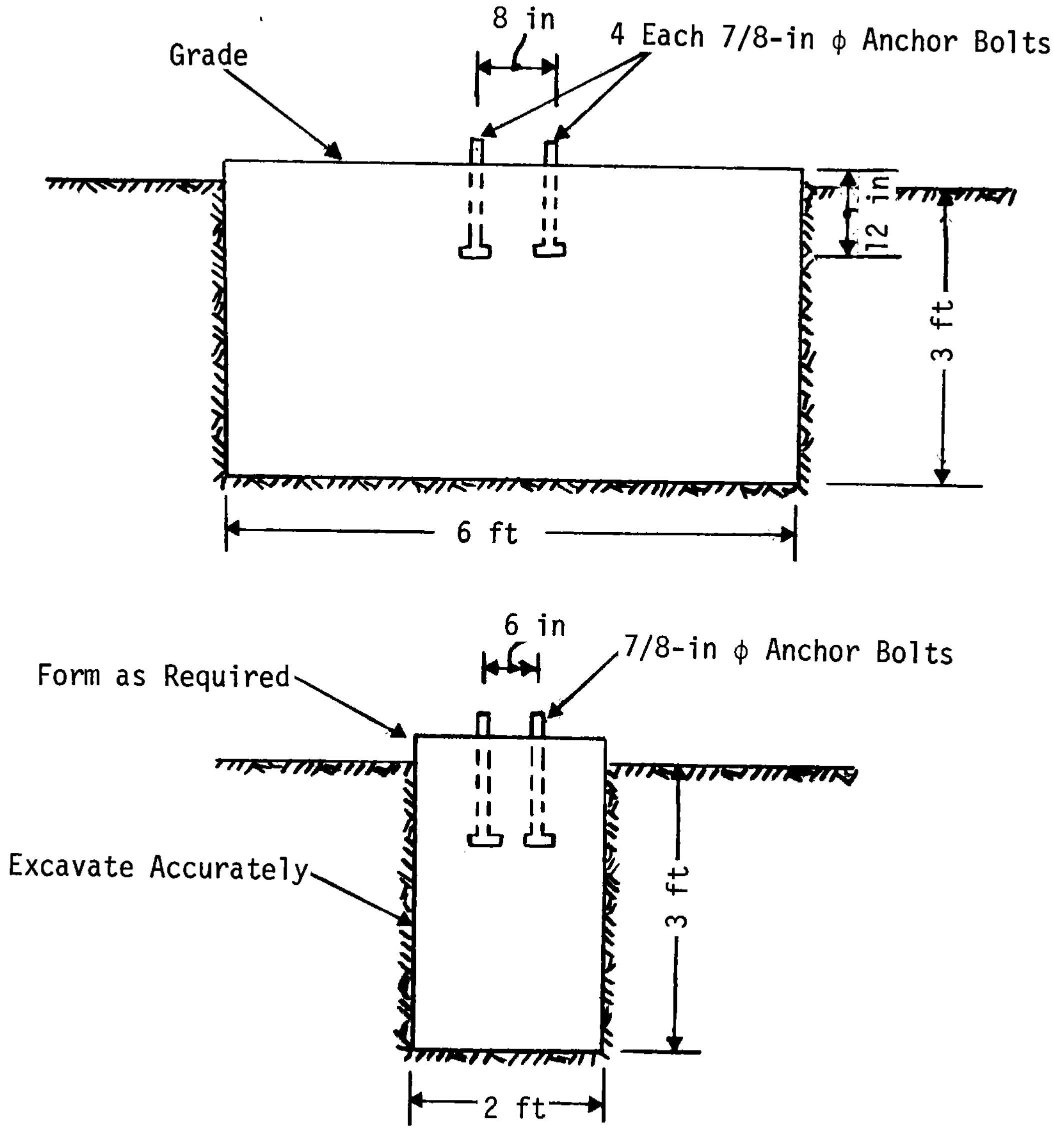


Figure 4b. Detailed Bent Design, *Typical* Site



Notes: f'_c = 2500 lb/in² Concrete
A307 Anchor Bolts

Figure 5. Detailed Footing Design, *Typical* or *Poor* Site

site preparation was required and that a backhoe could be utilized to accomplish most of the excavation. Minimum forming may be required to achieve the proper grade. The bottom of the excavation should be compacted. It is imperative that as little forming as possible be utilized as it will degrade the development of forces between the soil and concrete that are required to resist the upward component of the load. Note that no reinforcement is required.

A jig should be used to insure that the anchor bolts are located to the tolerances given in Section II-2. These tolerances should be easily attained utilizing normal construction practices. Shims can be used to attain final vertical alignment. Lateral alignment will be discussed in the next subsection.

5. LATERAL ALIGNMENT

With special precautions, each of the foundation systems presented in this section can be constructed such that the anchor bolts for the connection angles of the collector pedestal can be located to the tolerances indicated in Section II-2a. The construction contractor will be forced to utilize a jig to achieve these tolerances. However, any increase in costs will be more than offset by the elimination of the requirement for an adjustment plate. The system contractor must make provision for final lateral-alignment adjustments as shown in Figure 6. The long-term permanent displacements under maximum-loading conditions can be corrected by the same adjustments that were utilized for initial positioning.

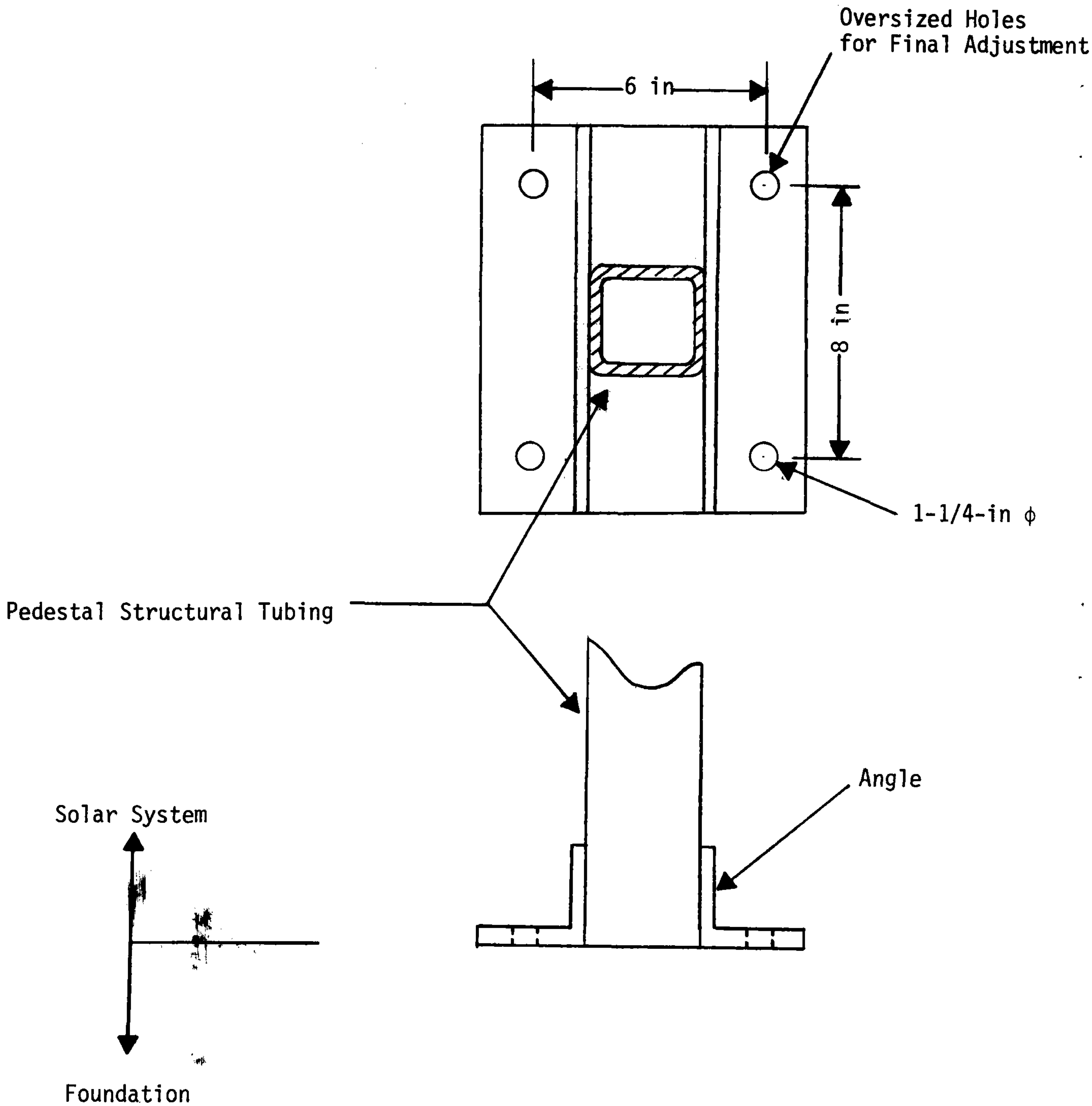


Figure 6. Pedestal Connection Angles

SECTION V
SUMMARY AND CONCLUSIONS

Ten preliminary foundation concepts were developed for typical single-axis-tracking solar collector systems to satisfy the foundation design criteria given in Section II. There were no standard design procedures available for designing short rigid piles subjected to inclined loads; therefore, a comprehensive theory was developed and is presented in this report. Three of the preliminary concepts were selected for detailed design:

1. Cylindrical Reinforced Concrete Piers
2. Bents
3. Rectangular Concrete Footing

The pier was found to be the most economical design of the 10 concepts and should be utilized whenever site conditions permit its construction. The rigid-pile theory developed in this report allows for a smaller, more cost-effective pier design than is utilized in existing systems. The rectangular footing will normally provide a reasonable, but more expensive, alternative for use at sites where the pier cannot be constructed because of extremely competent or coarse-grained subsurface material.

The tolerances for the anchor-bolt positions have been specified to eliminate the requirement for an adjustment plate. The construction contractor will be required to utilize a jig to achieve these tolerances. The equipment manufacturer can easily accommodate the remaining adjustments in the design of the pedestal connection angles.

It is felt that the design loads specified in Section II are conservative and the current wind tunnel test program being conducted by Sandia Corporation will provide data for specifying more reasonable loads for future designs. Reduction of design loads will result in smaller foundation dimensions, and estimated costs will decrease accordingly. The cylindrical pier design may not necessarily remain the most cost-effective solution for loading conditions significantly different from those utilized in the original designs.

The foundation test program currently being planned by Sandia Corporation should provide valuable data for evaluating the design procedures developed in this study. The geophysical parameters for the materials at the test site should be thoroughly documented to insure that a meaningful analysis of the test results can be accomplished.

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6. Wang, G.K., and Salmon, C.G., *Reinforced Concrete Design*, Second Edition, Intext Educational Publishers, 1973.

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APPENDIX A

COST ESTIMATES FOR PRELIMINARY DESIGNS

The following assumptions were made for calculating cost estimates:

1. Site within 50-mi radius of major city.
2. Minimum of 500 foundations per site.
3. Work performed by general contractor.
4. Volume of concrete x 1.15 to account for over-excavation, etc.

Preliminary design sketches are given in Figures 2a through 2e. Details of the cost estimate follow:

1. Cylindrical Reinforced Concrete Pier

	Typical Site		*Poor* Site	
Auger hole ($3.50/ft + $3.50)	L = 5 ft,	$ 21	L = 7½ ft,	$ 30
Reinforced concrete ($150/yd³) including labor, reinforcing, etc.	V_c = .30,	45	V_c = .56,	84
4 anchor bolts ($3 each) including labor		12		12
Total		$ 78		$126

2. Steel Pipe Column

Note: 12-in diameter standard-weight galvanized pipe weighs 50 lb/ft

	Typical Site		*Poor* Site	
Pipe column ($0.50/lb)	W = 325 lb,	$163	W = 600 lb,	$300
Installation ($5/ft)	L = 6.5 ft,	33	L = 12 ft,	60
Mounting plate (L.S.) including anchor bolts and field welding		15		15
Total		$211		$375

3. Rectangular Concrete Footing

Note: Same design is used for both *typical* and *poor* sites.

	Typical Site	*Poor* Site
Excavation ($25/yd^3) assume backhoe	$V = 1.53$, $ 38	
Concrete ($100/yd^3) unreinforced, including labor and minimum forming	$V_c = 1.53$, 153	
4 anchor bolts ($3 each) including labor	12	
Total	$203	

4. Rectangular Reinforced Concrete Pier

	Typical Site	*Poor* Site
Excavation ($200/yd^3) small deep hole with much hand work	$V = .22$, $ 44	$V = .45$, $ 90
Reinforced concrete ($150/yd^3)	$V_c = .24$, 37	$V_c = .45$, 68
4 anchor bolts ($3 each) including labor	12	12
Total	$ 93	$170

5. Bent

	Typical Site	*Poor* Site
Auger holes ($3.50/ft + $3.50)	2L = 10 ft, $ 42	2L = 14 ft, $ 56
Reinforced concrete ($150/yd^3) including labor, reinforing, etc.	$V_c = .18$, 27	$V_c = 1.06$, 159
Structural steel ($0.75/lb) W 6 x 15.5 + plates and bolts including welding	W = 57, 43	W = 69, 52
4 anchor bolts ($3 each) including labor	12	12
Total	$124	$279

6. Reinforced Concrete Mat

Note: Same design is used for both *typical* and *poor* sites.

		Typical Site		*Poor* Site
Site preparation (L.S.) minimum grading				\$ 20
Reinforced concrete (\$100/yd³) including labor, reinforcing, forming, etc. Mass pour			V_c = 2.13,	213
4 anchor bolts (\$3 each) including labor				12
Total				\$245

7. Steel Beam With Tiedowns

		Typical Site		*Poor* Site
Site preparation (L.S.) minimum grading		\$ 10		\$ 10
Structural steel (\$0.50/lb)	W = 120,	60	W = 120,	60
2 anchors and cable assemblies (L.S.)		44		76
Install anchors (\$3/ft)	L = 10,	30	L = 16,	48
Connection to W 6 x 12 (L.S.) material and labor		10		10
Total		\$154		\$204

8. Reinforced Concrete Pad With Tiedowns

		Typical Site		*Poor* Site
Site preparation (L.S.) assume backhoe		\$ 10		\$ 10
Reinforced concrete (\$150/yd³) including labor, reinforcing, etc.	V_c = .03,	5	V_c = .13,	20
2 anchors and cable assemblies (L.S.)		56		76
Install anchors (\$3/ft)	L = 12,	36	L = 16,	48
4 anchor bolts (\$3 each) including labor		12		12
2 cables and turnbuckles (L.S.)		10		10
Total		\$129		\$176

9. Earth Anchor With Tiedowns

		Typical Site		*Poor* Site
Helix earth anchor (L.S.)		$ 45		$ 60
Install helix (L.S.)		24		48
2 anchors and cable assemblies (L.S.)		44		76
Install anchors ($3/ft)	L = 10,	30	L = 16,	48
Head and field welding (L.S.)		20		20
Cables and turnbuckles (L.S.)		10		10
Total		$173		$262

10. Earth Anchors

	Typical Site	*Poor* Site
2 helix earth anchors (L.S.)	$100	$140
Install helices (L.S.)	36	60
Head (W 6 x 12) and field welding	25	25
Total	$161	$225

APPENDIX B

SHORT RIGID PILE SUBJECTED TO INCLINED ECCENTRIC LOAD

Figure B-1 illustrates a short rigid pile subjected to an eccentric load which was inclined at an arbitrary angle, θ. The objective of this appendix is to develop equations appropriate for designing these piles and for estimating the magnitude of the horizontal deflection at the ground surface.

Das and Seely (Ref. B-1) suggest an extension of an equation by Meyerhof (Ref. B-2) for short rigid piles subjected to inclined concentric loads. This extension develops the interaction equation further to include eccentric loads, as indicated by Equation B-1.

$$\frac{Q_{u\theta} \cos \theta}{Q_{uv}} + \left(\frac{Q_{u\theta} \sin \theta}{Q_{um}}\right)^2 = 1 \qquad \text{(B-1)}$$

where

$Q_{u\theta}$ = magnitude of inclined load x factor of safety
θ = angle of inclination, measured from vertical axis
Q_{uv} = gross ultimate resistance for $\theta = 0$
Q_{um} = gross ultimate resistance for $\theta = 90°$

The vertical uplift capacity of buried piles can be calculated from

$$Q_{uv} = r\, A_s + W \qquad \text{(B-2)}$$

B-1 Das, B.M., and Seely, G.R., "Uplift Capacity of Model Piles Under Oblique Loads," *Journal of the Geotechnical Engineering Division, ASCE*, Vol. 102, No. GT9, Technical Note, September 1976, pp. 1009-1013.

B-2 Meyerhof, G.G., "The Uplift Capacity of Foundations Under Oblique Loads," *Canadian Geotechnical Journal*, Vol. 10, No. 1, February 1973, pp. 64-70.

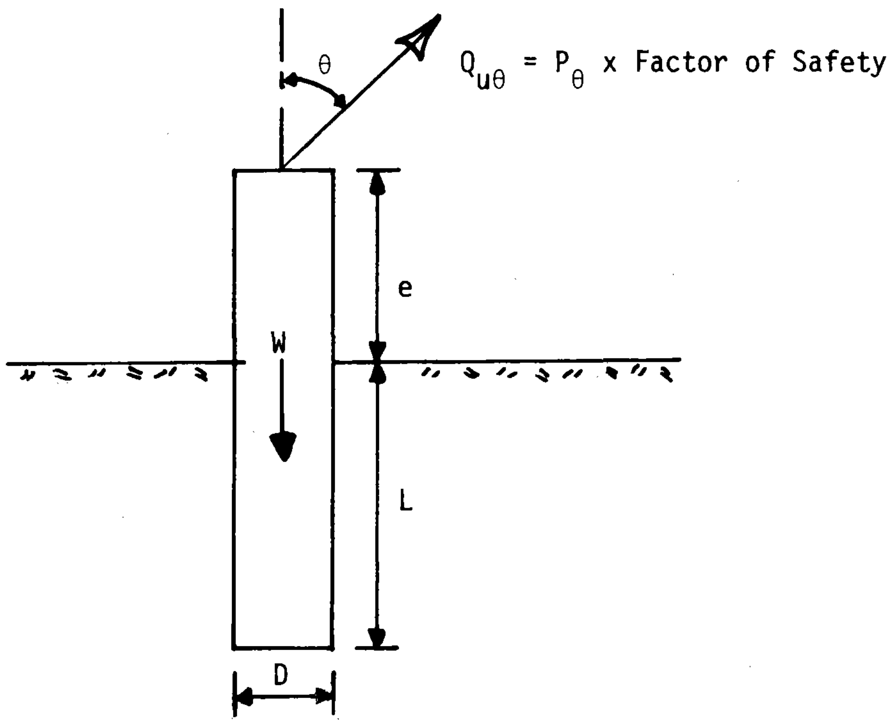

Figure B-1. Short Rigid Pile Subjected to Inclined Eccentric Load where

r = average unit resistance to uplift

A_s = embedded surface area

W = weight of pile

The average unit resistance to uplift is given by

$$r = K_c C_u + \frac{1}{2} K_u \bar{\gamma} L \tan \delta \qquad \text{(B-3)}$$

where

K_c and K_u = uplift coefficients

[K_c ranges from approximately 0.4 to 0.6 for cases of interest and Meyerhof (Ref. B-2) gives values of K_u = 2 and 5 for ϕ = 30 and 40 deg, respectively.]

C_u = cohesive strength = 1/2 unconfined compressive strength

$\bar{\gamma}$ = effective unit weight of soil

δ = skin friction parameter = 0.6 ϕ

ϕ = angle of internal friction

Q_{um} can be calculated from solutions given by Broms (Refs. B-3 and B-4). For cohesive soils, Figure B-2 defines the terms used in the following equations:

$$f = Q_{um}/9\ C_u\ D \qquad \text{(B-4)}$$

$$M^{+}_{max} = Q_{um}(e + 1.5\ D + 0.5\ f) \qquad \text{(B-5)}$$

$$= 2.25\ Dg^2\ C_u \qquad \text{(B-6)}$$

$$L = 1.5\ D + f + g \qquad \text{(B-7)}$$

B-3 Broms, B.B., "Lateral Resistance of Piles in Cohesive Soils," *Journal of the Soil Mechanics and Foundations Division, ASCE*, Vol. 90, No. SMZ, Proceedings Paper 3825, March 1964, pp. 27-63.

B-4 Broms, B.B., "Lateral Resistance of Piles in Cohesionless Soils," *Journal of the Soil Mechanics and Foundations Division, ASCE*, Vol. 90, No. SM3, Proceedings Paper 3909, May 1964, pp. 123-156.

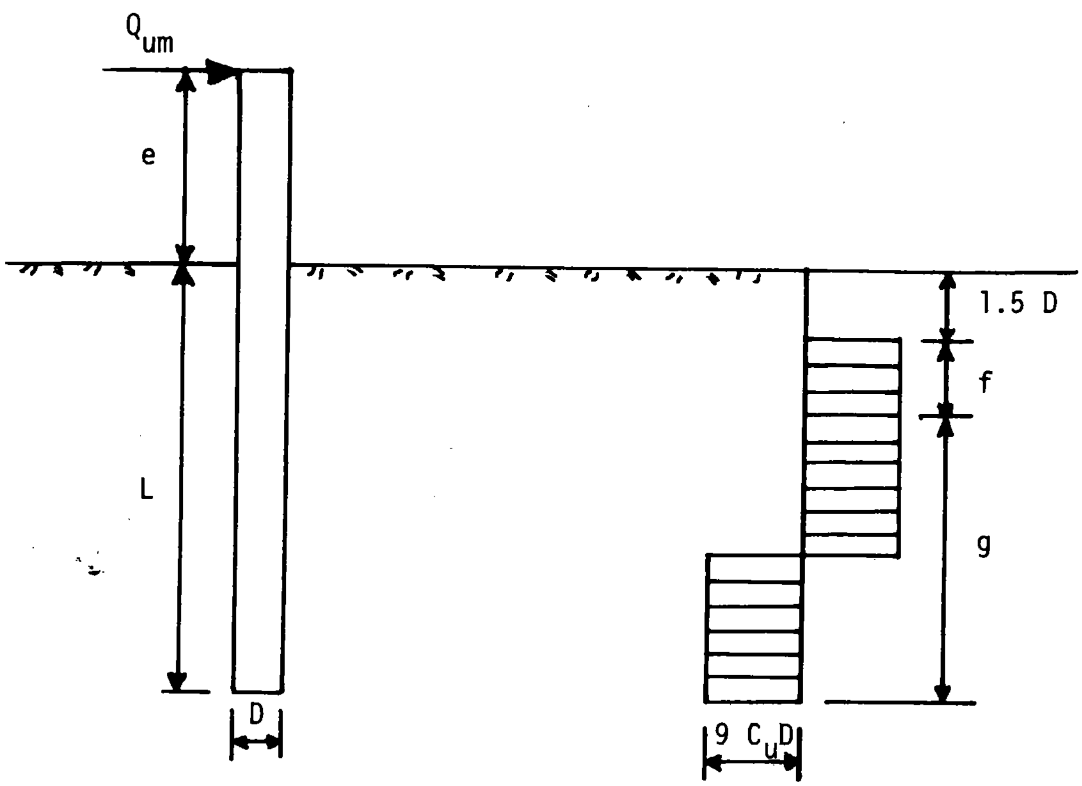

Figure B-2. Soil Reaction for a Short Rigid Pile in Cohesive Material

Dimensionless quantities are defined as follows:

$$\xi = Q_{um}/C_u D^2$$

$$\bar{e} = e/D$$

$$\bar{L} = L/D$$

Then Equations B-4 through B-7 can be combined to yield

$$\xi^2 + 36\xi\,[\bar{e} + \bar{L}/2 + 0.75] - 81\,[\bar{L}^2 - 3\bar{L} + 2.25] = 0 \qquad \text{(B-8)}$$

Equation B-8 can be used to solve for Q_{um} as a function of assumed values of D and L.

For granular soils, Figure B-3 defines the terms used in Equation B-9.

$$Q_{um} = \frac{0.5\,\bar{\gamma}\,DL^3\,K_p}{e + L} \qquad \text{(B-9)}$$

where

K_p = coefficient of passive earth pressure = $\dfrac{1 + \sin\phi}{1 - \sin\phi}$

References B-3 and B-4 can also be used to compute the transient lateral deflection at the ground surface, Y_o, under the maximum horizontal service load P_h, which is equal to $Q_{u\theta}$ sinθ/factor of safety (see Figure B-1).

For cohesive soils, Y_o is given by

$$Y_o = \frac{P_h}{DLK_q} + \frac{12.35\,P_h(e + L/2)}{D\,L^2\,K_m} \qquad \text{(B-10)}$$

The coefficients of soil reaction, K_q and K_m can be evaluated from

$$K_q = \frac{E_s}{m(1 - \mu_s{}^2)\,\sqrt{LD}}$$

and

$$K_m = \sqrt{10}\,K_q$$

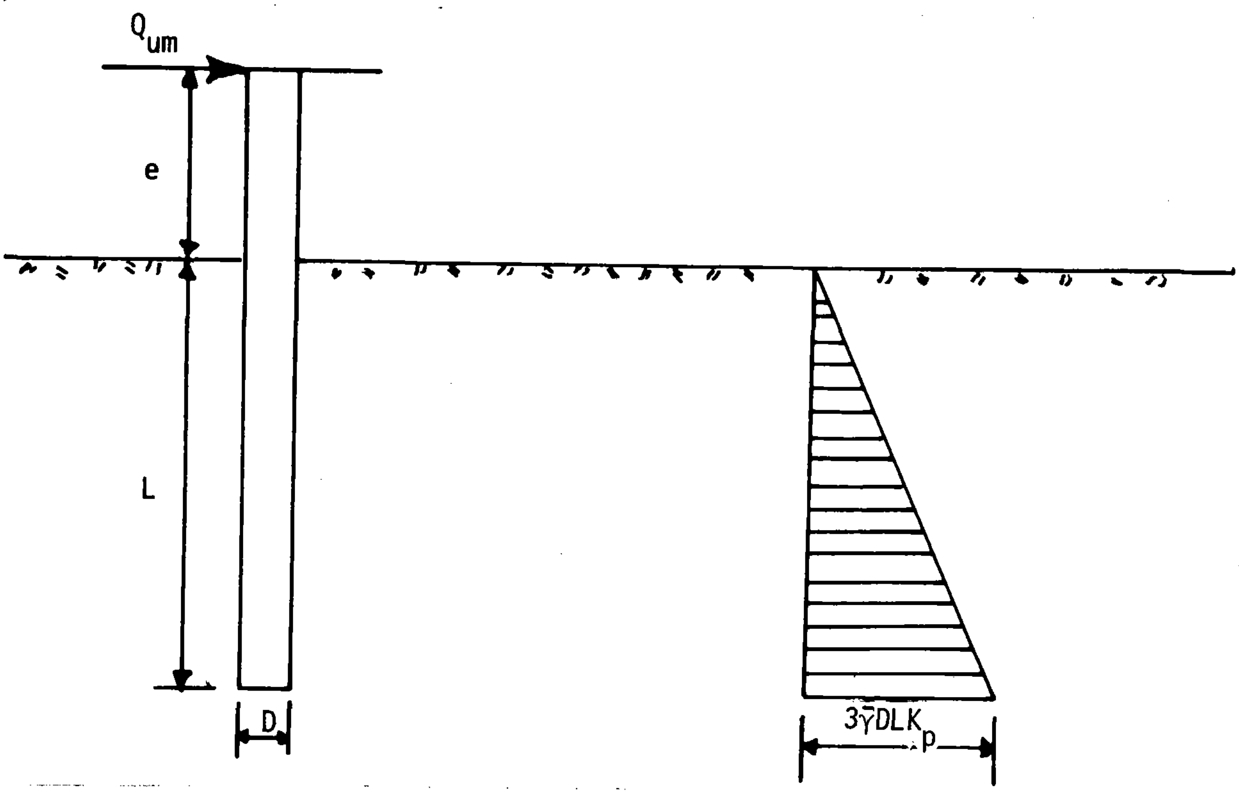

Figure B-3. Soil Reaction for a Short Rigid Pile in Granular Material where

E_s = soil modulus = 100 C_u

μ_s = Poisson's ratio of soil, assume 1/3

m = numerical factor

L/D	1.0	1.5	2	3	5	10	100
m	0.95	0.94	0.92	0.88	0.82	0.71	0.37

For granular soils, Y_o is given by

$$Y_o = \frac{18 \, P_h \, (1 + 1.33 \, e/L)}{L^2 \, n_h} \tag{B-11}$$

where

n_h = coefficient of horizontal subgrade reaction

	Coefficient n_h, Kip per ft^3		
Relative Density	Loose	Medium	Dense
Above Water Table	14	42	112
Below Water Table	8	28	68

Above the water table use n_h = 28 and 112 for ϕ = 30 and 40 deg, respectively.

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