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CHAPTER 9

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FOUNDATION DESIGN PROCEDURE

FOUNDATION DESIGN APPROACH

A foundation is the interfacing element between the superstructure and the underlying soil or rock. The loads transmitted by the foundation to the underlying soil must not cause soil shear failure or damaging settlement of the superstructure. It is essential to systematically consider various foundation types and to select the optimum alternative based on the superstructure requirements and the subsurface conditions.

The following design approach is recommended to determine the optimum foundation alternative.

1. Determine the foundation loads to be supported, structure layout, and special requirements such as limits on total and differential settlements, lateral loads, scour, seismic performance, and time constraints on construction. **This step is often partially overlooked or vaguely addressed. A complete knowledge of these issues is of paramount importance.**

2. Evaluate the subsurface exploration and the laboratory testing data. Ideally, the subsurface exploration and laboratory testing programs were performed with knowledge of the loads to be transmitted to, and supported by, the soil and/or rock materials.

3. Prepare a final soil profile and critical cross sections. Determine soil layers suitable or unsuitable for spread footings, pile foundations, or drilled shafts. Also consider if ground improvement techniques could be used to modify unsuitable layers into suitable support layers.

4. Consider and prepare alternative designs.

Shallow Foundations: (without ground improvement)	a. Spread footings. b. Mat foundations.
Shallow Foundations: (with ground improvement)	a. Spread footings. b. Mat foundations.
Deep Foundations:	a. Pile foundations. b. Drilled shafts.

   Table 9-1 summarizes shallow and deep foundation types and uses, as well as applicable and non-applicable soil conditions. There may be cases in which other foundations system may prove to be feasible (continuous flight auger piles, for example).

5. Prepare cost estimates for feasible alternative foundation designs including all associated substructure costs.

6. Select the optimum foundation alternative. Generally the most economical alternative should be selected and recommended. However, the ability of local construction forces, availability of materials and equipment, as well as environmental consideration/limitations should also be considered.

For major projects, if the estimated costs of feasible foundation alternatives (during the design stage) are within 15% of each other, then alternate foundation designs should be considered for inclusion in the contract documents.

Table 9-1 Foundation Types and Typical Uses*			
Foundation Type	Use	Applicable Soil Conditions	Non-suitable or Difficult Soil Conditions
Spread footings, Wall footings	Individual columns, walls, bridge piers	Any conditions where bearing capacity is adequate for the applied loads. Generally applicable in cases in which the bearing layer is within 10 feet of the proposed ground surface.	Any conditions where foundations are supported on soils subject to scour or liquefaction. Bearing layer located below groundwater table.
Mat Foundation	Same as spread and wall footings. Very heavy column loads. Usually reduces differential settlements and total settlements.	Generally soil bearing value is less than for spread footings. Over one-half area of structure covered by individual footings. Check settlements.	Same as for spread footings
Pile foundations (shaft resistance, toe resistance, or combination)	In groups to transfer heavy column and bridge loads to suitable soil/rock layers. Also to resist uplift and/or lateral loads.	Poor surface and near surface soils. Soil/rock suitable for load support within 15 to 150 feet of the ground surface. Check settlement of pile groups.	Shallow depth to hard stratum. Sites where pile driving vibrations or heave may adversely impact adjacent facilities. Boulder fields.
Drilled shafts (shaft resistance, toe resistance or combination)	Larger column loads than for piles. Cap sometimes eliminated by using drilled shafts as column extensions.	Poor surface and near surface soils. Soils and/or rock of suitable load support located within 25 to 300 feet of the ground surface.	Deep deposits of soft clays and loose, water-bearing, granular soils. Caving formations difficult to stabilize. Artesian conditions. Boulder fields.

*Modified after Bowles (1977)

CONSIDERATION OF SPREAD FOOTING FOUNDATION

The feasibility of using spread footings for foundation support should be considered in any foundation selection process. Spread footings are generally more economical than deep foundations (piles and drilled shafts); spread footings in conjunction with ground improvement techniques should also be considered. **Deep foundations should not be used indiscriminately for all subsurface conditions and for all structures**. There are subsurface conditions where pile foundations are very difficult and costly to install, and other conditions when they may not be necessary.

ESTABLISHMENT OF A NEED FOR A DEEP FOUNDATION

The first difficult problem facing the foundation designer is to establish whether or not the site conditions dictate that a deep foundation must be used. Vesic (1977) summarized typical situations in which piles may be needed. These typical situations as well as additional uses of deep foundations are shown in Figure 9-1.

Figure 9-1(a) shows the most common case in which the upper soil strata are too compressible or too weak to support heavy vertical loads. In this case, deep foundations transfer loads to a deeper dense stratum and act as toe bearing foundations. In the absence of a dense stratum within a reasonable depth, the loads must be gradually transferred, mainly through soil resistance along shaft, Figure 9-1(b). An important point to remember is that deep foundations transfer load through unsuitable layers to suitable layers. The foundation designer must define at what depth suitable soil layers begin the soil profile.

Deep foundations are frequently needed because of the relative inability of shallow footings to resist inclined, lateral, or uplift loads and overturning moments. Deep foundations resist uplift loads by shaft resistance, Figure 9-1(c). Lateral loads are resisted either by vertical deep foundations in bending, Figure 9-1 (d), or by groups are vertical and battered foundations, which combine the axial and lateral resistances of all deep foundations in the group, Figure 9-1(e). Lateral loads from overhead highway signs and noise walls may also be resisted by groups of deep foundations, Figure 9-1(f).

Deep foundations are often required when scour around footings could cause loss of bearing capacity at shallow depths, Figure 9-1(g). In this case the deep foundations must extend below the depth of scour and develop the full capacity in the support zone below the level of expected scour. FHWA scour guidelines (1991) require the geotechnical analysis of bridge foundations to be performed on the basis that all stream bed materials in the scour prism have been removed and are not available for bearing or lateral support. Costly damage and the need for future underpinning can be avoided by properly designing for scour conditions.

Soils subject to liquefaction in a seismic event may also dictate that a deep foundation be used, Figure 9-1(h). Seismic events can induce significant lateral loads to deep foundations. During a seismic event, liquefaction susceptible soils offer less lateral resistance as well as reduced shaft resistance to a deep foundation. Liquefaction effects on deep foundation performance must be considered for deep foundations in seismic areas.

Deep foundations are often used as fender systems to protect bridge piers from vessel impact, Figure 9-1(i). Fender systems sizes and groups configurations vary depending upon the magnitude of vessel impact forces to be resisted. In some cases, vessel impact loads must be resisted by the bridge pier foundation elements. Single deep foundations may also be used to support navigation aids.

In urban areas, deep foundations may occasionally be needed to support structures adjacent to locations where future excavations are planned or could occur, Figure 9-1(j). Use of shallow foundations in these situations could require foundations underpinning in conjunction with adjacent construction.

Deep foundations are used in areas of expansive or collapsible soils to resist undesirable seasonal movements of the foundations. Deep foundations under such conditions are designed to transfer foundation loads, including uplift or downdraft, to a level unaffected by seasonal moisture movements, Figure 9-1(k).

In many instances either a shallow or deep foundation alternative is technically feasible. Under these circumstances, an evaluation of the shallow foundation should include; (1) the dimensions and depth of shallow footings based on allowable bearing capacity, (2) the magnitude and time-rate of settlement under anticipated loads, and (3) detailed cost analysis including such factors as need for cofferdams, overall substructure cost, dewatering and foundation seals, construction time, construction risk and claims potential. A comparative analysis of feasible alternatives should have a significant role in final selection of the foundation type.

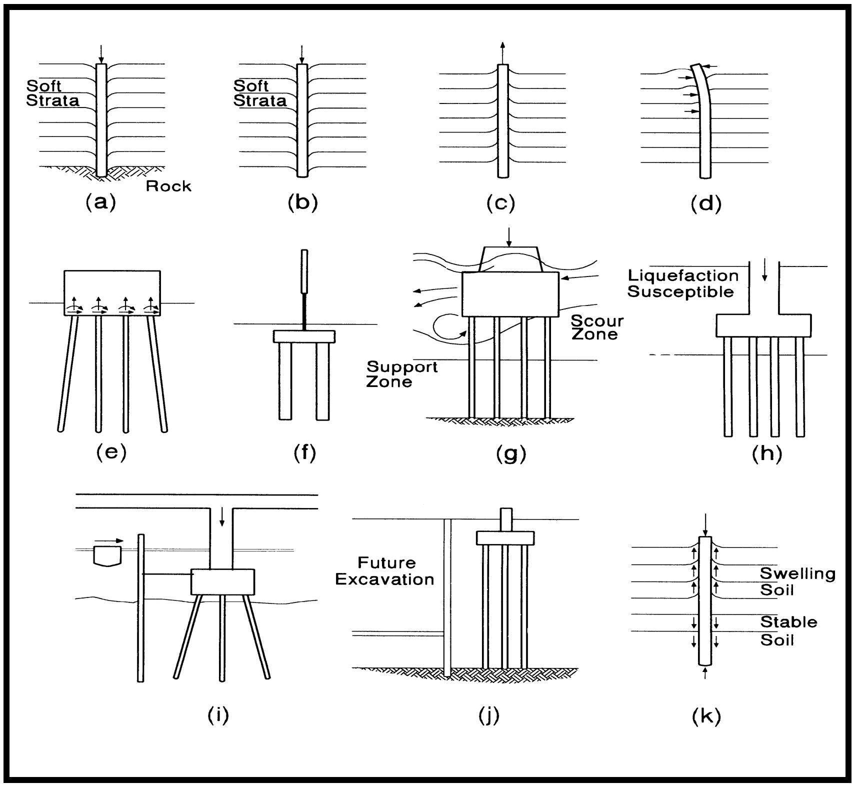

Figure 9-1 Situations in which Deep Foundations may be needed (Modified after Vesic, 1977)

ECONOMICS OF STRUCTURAL FOUNDATIONS

Foundation design and construction involve engineering, economic and constructability considerations pertinent to the particular site in question. The engineering considerations are addressed by determining the foundation loads and performance requirements, development of the foundation design parameters and design analysis. The design analysis coupled with past experience will provide several feasible foundation alternatives.

The next step involves an economics evaluation of potential foundations. Several foundation alternatives may be satisfactory for the subsurface conditions while also meeting superstructure requirements. However, of all the foundation alternatives, generally only one will have the least possible cost.

Last, the constructability of a potential foundation must be considered. A potential foundation, solution may appear to be the most economical from purely a design perspective, but may not be most economical when limitations on construction activities are fully considered. Constructability issues such as impact on adjacent structures, equipment, access, methods, work hours, etc., must be considered in design.

ALTERNATE FOUNDATIONS CONSIDERATIONS

To determine the most feasible foundation alternatives, both shallow foundations and deep foundations should be considered. Deep foundation alternatives include both piles and drilled shafts. Proprietary and other deep foundations systems should not be excluded as they may be the most economical alternative in a given condition. Additional details on spread footings for highway bridges may be found in FHWA-IF-02-054 (GEC No. 6) “Shallow Foundations”. The FHWA publication FHWA-NHI-10-016 (GEC N0. 10) by Brown, Turner and Castelli (2010) summarizes design methods and construction procedures for drilled shafts.

A cost evaluation of all feasible foundation alternatives is essential in the selection of the optimum foundation system. Pile foundation cost data for completed projects can be obtained from statewide average bid prices available from state transportation agencies. Foundation contractors can also provide rough estimates on foundation items.

Cost analyses of all feasible alternatives may lead to the elimination of some foundations qualified under the engineering study. Other factors that must be considered in the final foundation selection are availability of materials and equipment, local contractor and construction force experience, as well as any environmental limitations/considerations on construction access or activities.

For many projects, if the estimated costs of alternatives during the design stage are within 15% of each other, then alternate foundation designs should be considered for inclusion in the contract documents. If an alternate design is included in the contract documents, both designs should be adequately detailed. For example, if two pile foundation alternatives are detailed, the bid quantity pile lengths should reflect the estimated pile lengths for each alternative. Otherwise, material costs and not the installed foundation cost will likely determine the low bid. Use of alternate foundation designs will generally provide the most cost effective foundation system.

As noted earlier, proprietary pile types should not be routinely excluded from consideration. In a given soil condition, a proprietary system may be the most economical foundation type. Therefore, a proprietary system should be considered as a viable foundation alternate when design analyses indicate the cost to be within 15% of a conventional design. A conventional design alternate should generally be included with a proprietary design alternate in the final project documents to stimulate competition.

USE OF VALUE ENGINEERING PROPOSALS

Value engineering is a cost-saving technique that can be used either in the pre-bid or post-bid stage of a contract. Value engineering consists of a five step logical thought process used to obtain the desired performance for the lowest cost achievable. The five steps may be described as follows:

1. Information gathering.

2. Information analysis to understand the problem.

3. Creative thinking to arrive at alternatives giving the same performance at lower costs.

4. Systematic judging of the result from step 3.

5. Detailing of selected alternatives from step 4.

Value engineering can readily be applied to foundation engineering by allowing the use of value engineering change proposals in design or construction contracts. The obvious benefit of value engineering to the owner is a lower cost foundation. The consultant or contractor reward for an alternate foundation solution is typically a percentage of the cost savings realized by the owner.

For value engineering to be successful, the owner must be assured that the foundation performance criteria remain satisfied. This requires the owner to engage knowledgeable experts to review and comment on submittals as well as to be actively involved in resolution of technical details. In some cases, design verification testing or more sophisticated construction control may be required in order to confirm foundation performance criteria. Lastly, the review of submitted proposals must also be completed in a reasonable time period.

Significant cost savings can result from value engineering. However, the cost savings should not be achieved by acceptance of unproven pile types, splices, etc. Proposed substitutions should be of equivalent quality and have a documented performance record in similar foundation installation conditions.

VDOT's Value Engineering requirements can be found in the Road and Bridge Specifications.

DESIGN-BUILD PROPOSALS

Another potential cost-saving method is the use of design-build proposals. In this approach, the owner details the general project scope and performance requirements and solicits design-build proposals. New cost effective solutions may emerge from the design-build method since multiple firms are looking at the design and construction issues rather than a single designer. The design-build method also allows contractors to use their knowledge of special equipment or procedures. In design-build projects, it is important for the owner to understand and clearly communicate the project scope, performance requirements, and desired end product as well as method of measurement for payment. Failure to do so may result in a constructed product not meeting the owner's expectations or failing to meet the agreed-upon budget.

OVERVIEW OF PILE FOUNDATION DESIGN

DESIGN OF PILE FOUNDATIONS

As stated by Professor R.B. Peck, “Driving piles for a foundation is a crude and brutal process.” The interactions among the piles and the surrounding soil are complex. Insertion of piles generally alters the character of the soil and intense strains are set up locally near the piles. The nonhomogenity of soils, along with the effects of the pile group and pile shape, add further difficulties to the understanding of soil-pile interaction.

Broad generalizations about pile behavior are unrealistic. An understanding of the significance of several factors involved is required to be successful in the design of pile foundations. Because of the inherent complexities of pile behavior, it is necessary to use practical, semi-empirical methods of design, and to focus attention on significant factors rather than minor or peripheral details. The foundation engineer must have a thorough understanding of foundation loads, subsurface conditions including soil/rock properties and behavior, the significance or special design events, foundation performance criteria, and current practices in foundation design and construction in the area where the work is to be done to arrive at the optimum foundation solution.

CONSTRUCTION OF PILE FOUNDATIONS

Construction of a successful driven pile foundation that meets the design objectives depends on relating the requirements of the static analysis methods presented on the plans to the dynamic methods of field installation and construction control. The tools for obtaining such a foundation must be explicitly incorporated into the plans and specifications as well as included in the contract administration of the project.

It is important that a pile foundation be installed to meet the design requirements for compressive, lateral and uplift capacity. This may dictate driving piles for a required ultimate capacity or to a predetermined length established by the designer. It is equally important to avoid pile damage or foundation cost overruns by excessive driving. These objectives can all be satisfactorily achieved by use of wave equation analysis, dynamic monitoring of pile driving, and in some cases, static load testing. Commonly used dynamic formulas, such as Engineering New formula, have proven unreliable as pile capacities increased and more sophisticated pile installation equipment was routinely used by contractors.

Knowledgeable construction supervision and inspection are the keys to proper installation of piles. State-of-the art designs and detailed plans and specifications must be coupled with good construction supervision to achieve desired results.

Post construction review of pile driving results versus predictions regarding pile driving resistances, pile length, field problems, and load test capacities is essential. These reviews add to the experience of all engineers involved on the project and will enhance their skills for future projects.

GEOTECHNICAL INVOLVEMENT (PILE FOUNDATIONS)

The input of an experienced geotechnical engineer from the planning stage through project design and construction is essential to produce a successful driven pile foundation. The geotechnical engineer who specializes in foundation design is the most knowledgeable person for selecting the pile type, estimating pile length, and choosing the most appropriate method to determine ultimate pile capacity. Therefore, the geotechnical engineer should be involved throughout the design and construction process. In some project phases, i.e. preliminary explorations, preliminary design, and final design, the geotechnical engineer will have significant involvement. In other project phases, such as construction, and post-construction review, the geotechnical engineer’s involvement may be more of a technical services role. The geotechnical engineer’s involvement provides the needed continuity of design personnel in dealing with design issues through the construction stage.

DRIVEN PILE DESIGN-CONSTRUCTION PROCESS

The driven pile design and construction process has aspects that are unique in all of structural design. Because the driving characteristics are related to pile capacity for most soils, they can be used to improve the accuracy of the pile capacity estimate. In general, the various methods of determining pile capacity from dynamic data such as driving resistance with wave equation analysis and dynamic measurements are considerably more accurate than the static analysis methods based on subsurface exploration information. Furthermore, pile driveability is a very important aspect of the process and must be considered during the design phase. If the design is completed, a contractor is selected, and then the piles cannot be driven as designed, large costs can be generated. It is absolutely essential that the design and construction phased be linked in a way that does not exist elsewhere in construction.

The driven pile design-construction process is outlined in the flow chart of Figure 9-2. This flow chart will be discussed block-by-block using the number in the blocks as a reference and it will serve to guide the designer through all of the tasks that must be completed.

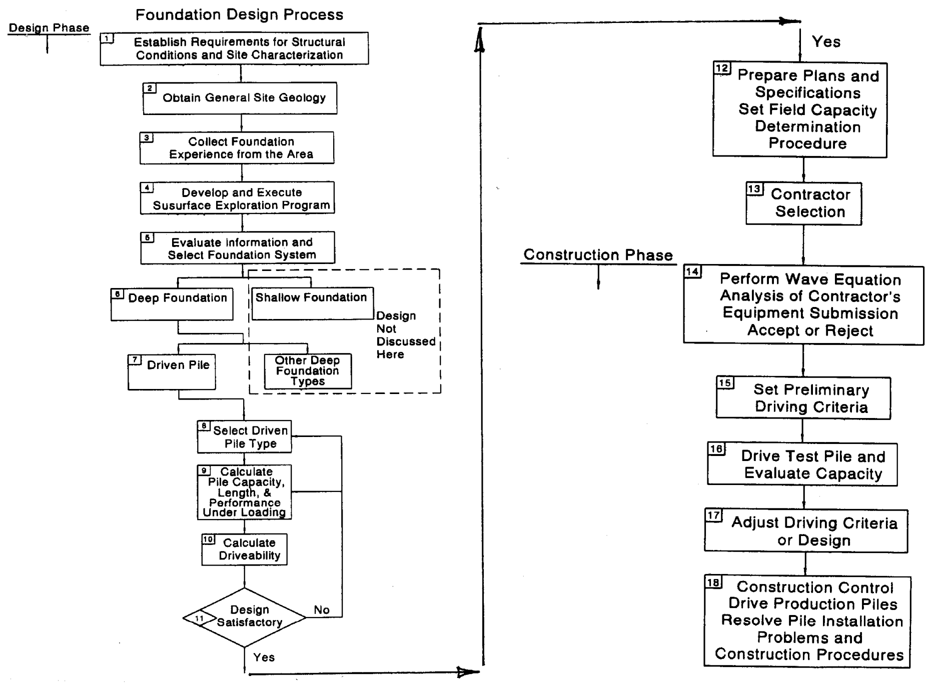

Fig. 9-2

Block 1: Establish Requirements for Structural Conditions and Site Characterization

The first step in the entire process is to determine the general structural requirements.

1. Is the project a new bridge, a replacement bridge, a bridge renovation, a retaining wall, a noise wall, or sign or light standard?

2. Will the project be constructed in phases or all at one time?

3. What are the general structure layout and approach grades?

4. What are the surficial site characteristics?

5. Is the structure subjected to any special design events such as seismic, scour, debris, vessel impact, etc? If there are special design events, the design requirements for the event should be reviewed at this stage so that these considerations can be factored into the site investigation.

6. Are there possible modifications in the structure that may be desirable for the site under consideration?

7. What are the approximate foundation loads? Are there deformation or deflection limitations beyond the usual requirements?

Block 2: Obtain General Site Geology

A great deal can be learned about the foundation requirements with even a very general understanding of the site geology. For small structures, this may involve only a very superficial investigation such as a visit to the site. The foundation design for very large structures may require extensive geologic studies.

Block 3: Collect Foundation Experience from the Area

Frequently information is available on foundations that have been constructed in the area (as-built bridge plans, for example). This information can be of assistance in avoiding problems. Both subsurface exploration information and foundation construction experience should be sought prior to selecting the foundation type.

Block 4: Develop and Execute Subsurface Exploration Program

Based on the information obtained in Blocks 1-3 it is possible to make decisions regarding the necessary information that must be obtained at the site. The program must meet the needs of the design problem that is to be solved at a cost consistent with the size of the structure. The subsurface exploration program as well as the appropriate laboratory testing must be selected. The results of the subsurface exploration program and the laboratory testing are used to prepare a subsurface profile and identify critical cross sections.

Block 5: Evaluate Information and Select Foundation System

The information collected in Blocks 1-4 must be evaluated and a foundation system selected. The first question to be decided is whether a shallow or a deep foundation is required. This question will be answered based primarily on the strength and compressibility of the site soils, the proposed loading conditions, and the project performance criteria. If settlement is not a problem for the structure, then a shallow foundation will probably be the most economical solution.

Ground improvement techniques in conjunction with shallow foundations should be evaluated. Shallow and deep foundation interaction with approach embankments must also be considered. If the performance of a shallow foundation exceeds the structure performance criteria, a deep foundation must be used. Refined foundation loading information and performance criteria should be established at this time. In Block 1, this issue was considered. Probably the result of that effort has matured in the intervening time (which might be quite long for some projects) and better defined foundation loads and performance criteria should now be available. The geotechnical engineer must obtain a completely defined and unambiguous set of foundation loads and performance requirements in order to proceed through the foundation design.

Block 6: Deep Foundation

The decision among deep foundation types is now generally divided between driven piles and drilled shafts. What is really intended is the difference between driven piles and all other deep foundation systems. These other deep foundations systems have been called a drilled shaft but would also include auger cast piles, micropiles and drilled-in deep foundation systems. The questions that must be answered in deciding between driven piles and other deep foundation systems will center on the relative costs and availability of possible systems. In addition, constructability must be considered.

Blocks 7 and 8: Driven Pile – Select Driven Pile Type

At this point on the flow chart, the primary concern is for the design of a driven pile foundation. The pile type must be selected consistent with the applied load per pile. Consider this problem. The general magnitude of the column or pier loads is known from the information obtained in Blocks 1 and 5. However, a large number of combinations of pile capacities and pile types can satisfy the design requirements. Should twenty, 100 ton capacity piles be used to carry a 2000 ton load, or would it be better to use ten, 200 ton capacity piles? This decision should consider both the structural capacity of a pile and the realistic geotechnical capacities of the pile type for the soil conditions at the site, the cost of the available alternative piles, and the capability of available construction contractors to drive the selected pile. Of course, there are many geotechnical factors that must also be considered.

At this stage the loads must be firmly established. In Block 1, approximate loads were determined. At that time the other aspects of the total structural design were probably not sufficiently advanced to establish the final design loads. By the time that Block 5 has been reached the structural engineer should have finalized the various loads. One of the most common inadequacies that is discovered when foundation problems arise is that the design loads were never really accurately defined.

In the former use of the dynamic formula, the pile load specified was a design or working load since a factor of safety was contained in the formula. Modern methods of pile capacity determination **always** use ultimate loads with a factor of safety selected and applied. This should also be made clear in the job specifications so that the contractor has no question regarding the driving requirements.

If there are special design events to be considered, they must be included in the determination of the loads. Vessel impact will be evaluated primarily by the structural engineer and the results of that analysis will give pile design loads for this case. There may be stiffness considerations in dealing with vessel impact since the design requirement is basically a requirement that some vessel impact energy be absorbed.

Scour presents a different requirement. The loads due to the forces from the stream must be determined as specified in the AASHTO Standard Specification for Highway Bridges. In the design process, it must be assured that after scour the pile will still have adequate capacity.

In many locations in the country, seismic loads will be an important contributor to some of the critical pile load conditions. Since the 1971 San Fernando Earthquake, much more emphasis has been placed on seismic design considerations in the design of highway bridges. The AASHTO Standard Specifications for Highway Bridges has been substantially expanded to improve the determination of the seismic loads. Usually the structural engineer will determine the seismic requirements. Frequently the behavior or the selected pile design will affect the structural response and hence the pile design loads. In this case, there will be another loop in the design process that includes the structural engineer. The geotechnical engineer should review the seismic design requirements of the AASHTO Bridge Design Specification for a general understanding of the design approach.

Block 9: Calculate Pile Length, Capacity, and Performance.

For the selected pile type, perform static analyses to determine the length necessary to provide the required compression, uplift and lateral load capacity and to meet performance criteria. It may be necessary to change pile type or number of piles at this stage.

Block 10: Calculate Driveability

At this point, the proposed pile type and length have been chosen to meet the foundation loading and performance requirements. However, the design is not complete until it can be verified that the chosen pile can be driven to the required capacity and penetration depth at a reasonable driving resistance without excessive driving stresses. This analysis is performed using the wave equation program. All of the necessary information is available except the hammer selection. Since the hammer to be used on the job will only be known after the contractor is selected, possible hammers must be tried to make sure that the pile is driveable to the capacity and depth required. The driveability analysis may demonstrate that a minimum hammer energy and minimum ram weight be mandated on the plans.

Block 11: Design Satisfactory

At this point in the process, all aspects of the design should be reviewed and if changes are indicated, the flow chart that is re-entered at some earlier point and a new design is developed.

Block 12: Prepare Plans and Specifications, Set Field Capacity Determination Procedure.

When the design has been finalized, plans and specifications can be prepared and the procedures that will be used to verify pile capacity can be defined. It is important that all of the quality control procedures are clearly defined for the bidders to avoid claims after construction is underway.

Block 13: Contractor Selection

After the bidding process is complete, a successful contractor is selected.

Block 14: Perform Wave Equation Analysis of Contractor's Equipment Submission

At this point the engineering effort shifts to the field. The contractor will submit a description of the pile driving equipment that he intends to use on the job for the engineer's evaluation. Wave equation analysis is performed to determine the driving resistance that must be achieved in the field to meet the required capacity and pile penetration depth. Driving stresses are determined and evaluated. If all conditions are satisfactory, the equipment is approved for driving the test piles only. It is important to remember that, because the wave equation analysis requires several assumptions, it is still an approximate model of the hammer-pile-soil system.

On smaller projects, a dynamic formula may be used to evaluate driveability and the Gates Formula should be used. If a dynamic formula is used, then driveability and hammer selection will be used on the driving resistance only, since stresses are not determined.

Block 15: Set Preliminary Driving Criteria

Based on the results of the wave equation analysis of Block 14 (or the Gates Formula) and any other requirements in the design, the preliminary driving criteria can be set.

Block 16: Drive Test Pile and Evaluate Capacity

The test pile(s) are driven to the preliminary criteria developed in Block 15. Driving requirements may be defined by penetration, driving resistance, dynamic monitoring results or a combination of these conditions. The capacity can be evaluated by driving resistance from wave equation analysis, the results of dynamic monitoring, static load test, the Gates Formula, or a combination of these.

Block 17: Adjust Driving Criteria or Design

At this stage the final conditions can be set or, if test results from Block 16 indicate the capacity is inadequate, the driving criteria may have to be changed. In a few cases, it may be necessary to make changes in the design as far back as Block 8. If major changes are required, it will be necessary to repeat Blocks 14, 15 and 16.

In some cases, it is desirable to perform preliminary field testing before final design. When the job is very large and the soil conditions are difficult, it may be possible to achieve substantial cost savings by having results from a design stage test pile program, including actual driving records at the site, as part of the bid package.

Block 18: Construction Control

After the driving criteria are set, the production pile driving begins. Quality control and assurance procedures have been established and are applied. Problems may arise and must be handled as they occur in a timely fashion.

SELECTION OF PILE TYPE

The selection of appropriate pile types for any project involves the consideration of several design and installation factors including pile characteristics, subsurface conditions and performance criteria. Figure 9-3 shows several pile classifications. Pile selection should be based on the factors listed in Tables 9-2, 9-3, and 9-4. Table 9-2 summarizes typical pile characteristics and uses. Table 9-3 provides pile type recommendations for various subsurface conditions. Table 9-4 presents the placement effects of pile shape characteristics.

In addition to the considerations provided in the tables, the problems posed by the specific project location and topography must be considered in any pile selection process. Following are some of the usually encountered problems:

1. Driven piles may cause vibration damage to adjacent structures or facilities.

2. Remote areas may restrict driving equipment size and, therefore, pile size.

3. Local availability of certain materials and capability of contractors may have decisive effects on pile selection.

4. Waterborne operations and transportation limitations may dictate use of shorter pile sections due to pile handling restrictions.

5. Steep terrain may make the use of certain pile equipment costly or impossible.

Although one pile type may emerge as the only logical choice for a given set of conditions, more often several different types may meet all the requirements for a particular structure. In such cases, the final choice should be made on the basis of a cost analysis that assesses the over-all cost of alternatives. This would include uncertainties in execution, time delays, cost of load testing programs, as well as differences in the cost of pile caps and other elements of the structure that may differ among alternatives. For major projects, alternate foundation designs should be considered for inclusion in the contract documents if there is a potential for cost savings.

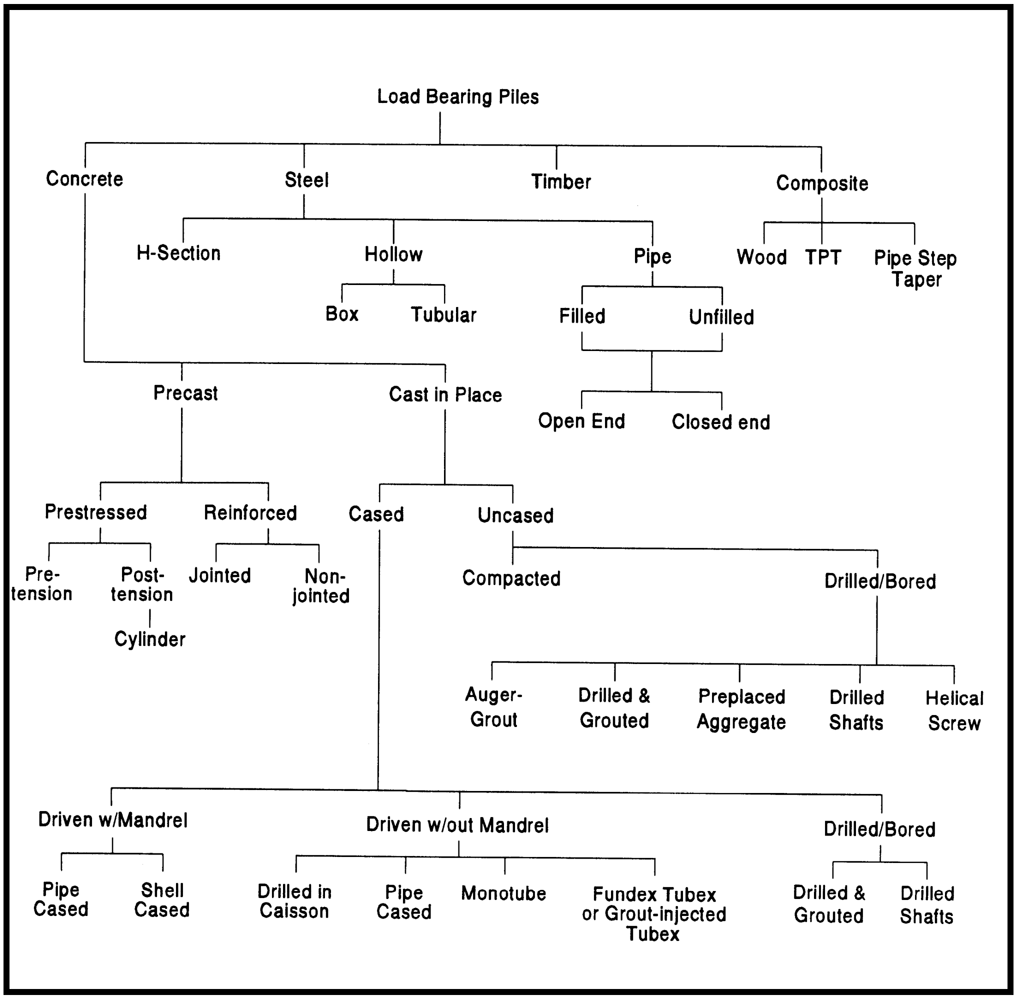

Fig. 9-3 Pile Classification

Table 9 - 2 SUMMARY OF PILES

Pile Type	Timber
Typical Lengths	15 to 60 ft.
Material Specifications	ASTM D25 AWPA-C3 (if used)
Maximum Stresses	See File No. 09.02- 8
Typical Axial Design Loads	10 to 50 tons
Disadvantages	• Difficult to splice • Vulnerable to damage by hard driving; both pile head and toe may need to protection • Intermittently submerged piles are vulnerable to decay unless treated
Advantages	• Comparatively low in initial cost • Permanently submerged piles are resistant to decay • Easy to handle
Remarks	• Best suited for friction piles in granular material

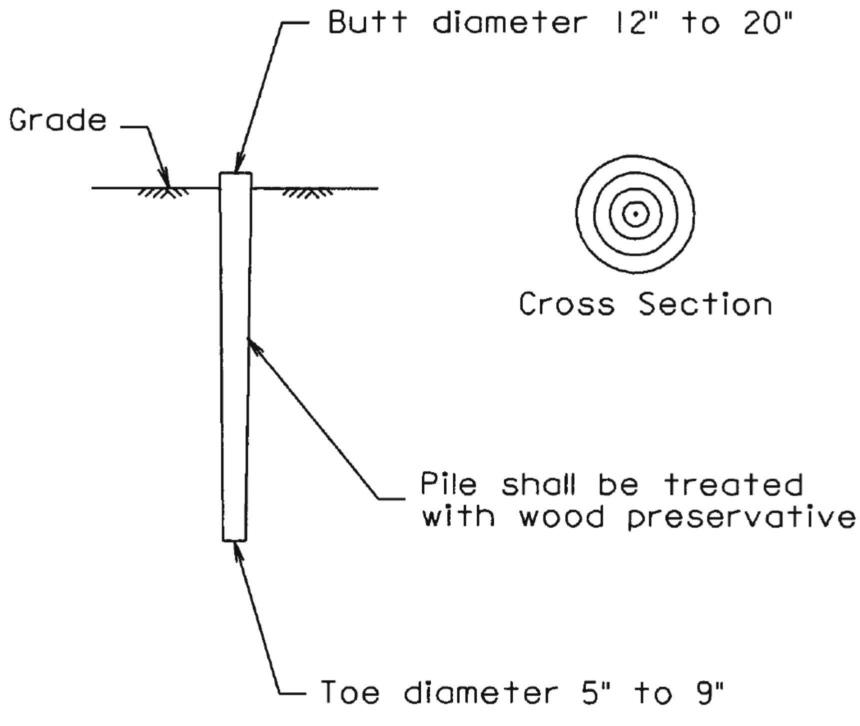

Table modified and reproduced from NAVFAC DM 7.2 (1982)

Table 9 - 2 (con't) SUMMARY OF PILES

Pile Type	Steel (HP - sections)
Typical Lengths	15 to 100 ft.
Material Specifications	ASTM A36 or A572, Grade 50
Maximum Stresses	See File No. 09.02- 4
Typical Axial Design Loads	45 to 225 tons
Disadvantages	• Vulnerable to corrosion where exposed HP section may be damaged or deflected by major obstructions • Not recommended as a friction pile in granular material
Advantages	• Easy to splice • Available in various lengths and sizes • High capacity • Small displacement • Able to penetrate light obstructions
Remarks	• Best suited for toe bearing on rock • Pile toe protection may be needed for penetration through hard obstructions or where soft rock is present

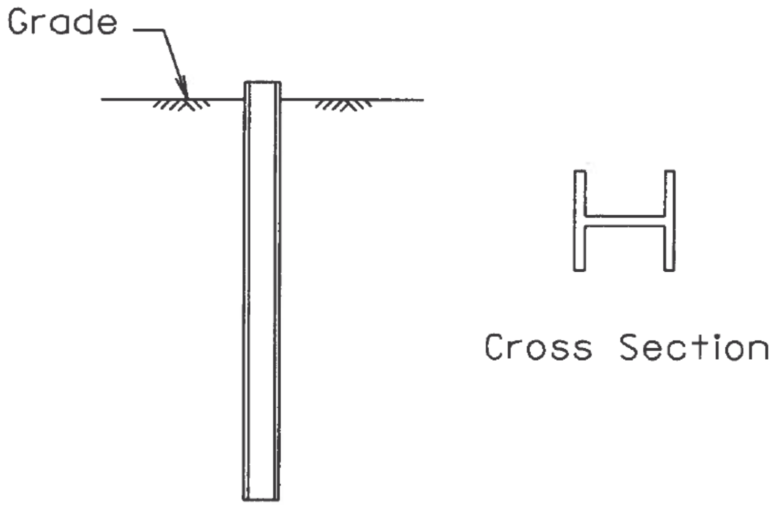

Table modified and reproduced from NAVFAC DM 7.2 (1982)

Table 9 - 2 (con't) SUMMARY OF PILES

Pile Type	Steel Pipe Piles
Typical Lengths	30 to 130 ft. or more
Material Specifications	ASTM A252 (for pipe) ACI 318 (for concrete, if filled) ASTM A36 or A572, Grade 50 (for core, if used)
Maximum Stresses	See File No. 09.02- 5 and No. 09.02- 6
Typical Axial Design Loads	90 to 280 tons (with or without concrete fill and without core) 560 to 1700 tons (concrete filled with cores)
Disadvantages	• Displacement for closed-ended pipe • Open-ended not recommended as a friction pile in granular soil
Advantages	• Best control during installation • Low displacement for open-ended installation • Open-ended pipe is best against obstructions • Piles can be cleaned out and driven further • High load capacities • Easy to splice
Remarks	• Provides high bending resistance where unsupported length is loaded laterally.

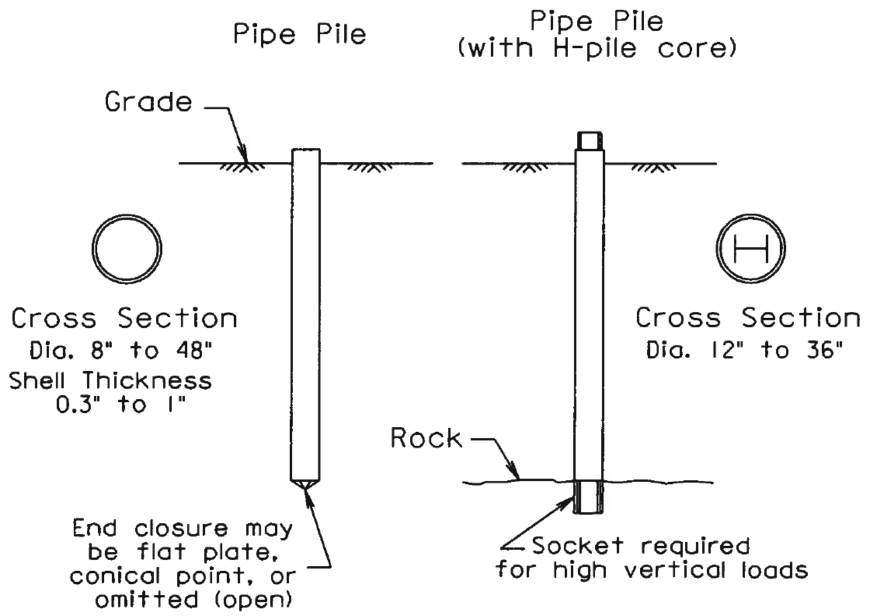

Table modified and reproduced from NAVFAC DM 7.2 (1982)

Table 9 - 2 (con't) SUMMARY OF PILES	
Pile Type	Prestressed Concrete
Typical Lengths	30 to 130 ft.
Material Specifications	ACI 318 (for concrete) ASTM A82, A615, A722, and A884 (for reinforcing steel) ASTM A416, A421 and A882 (for prestressing)
Maximum Stresses	See File No. 09.02- 7
Typical Axial Design Loads	45 to 500 tons
Disadvantages	• Vulnerable to handling damage. • Relatively high breakage rate, especially when spliced • High initial cost • Considerable displacement • Difficult to splice
Advantages	• High load capacities • Corrosion resistance obtainable • Hard driving possible
Remarks	• Cylinder piles are well suited for bending resistance.

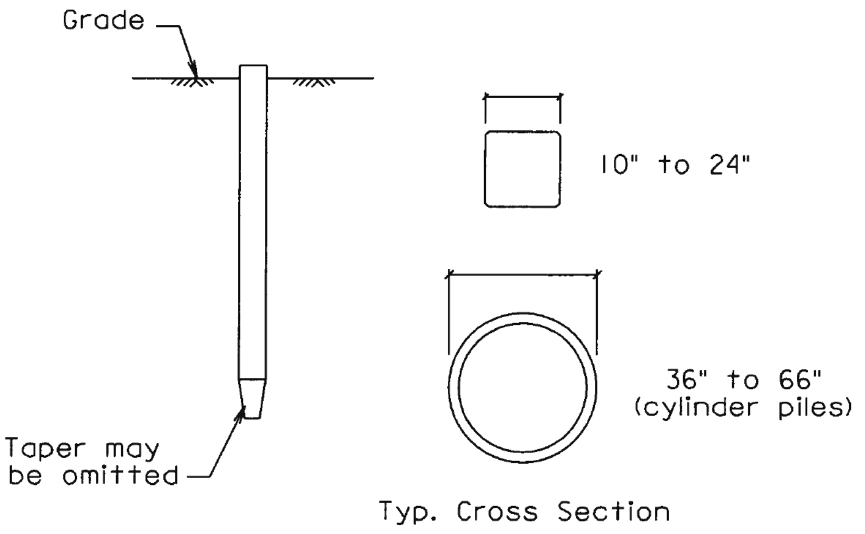

Table modified and reproduced from NAVFAC DM 7.2 (1982)

Table 9 - 2 (con't) SUMMARY OF PILES

Pile Type	Cast-In-Place (CIP) Concrete (Mandrel-driven Shell)
Typical Lengths	10 to 80 ft.
Material Specifications	ACI 318 (for concrete)
Maximum Stresses	See File No. 09.02- 6 (concrete only)
Typical Axial Design Loads	45 to 160 tons
Disadvantages	• Difficult to splice after concreting • Redriving not recommended • Thin shell vulnerable during driving to excessive earth pressure or impact • Considerable displacement
Advantages	• Initial economy • Tapered sections provide higher resistance in granular soil than uniform piles • Can be inspected after driving • Relatively less waste of steel • Can be designed as toe bearing or friction pile
Remarks	• Best suited as friction piles in granular materials

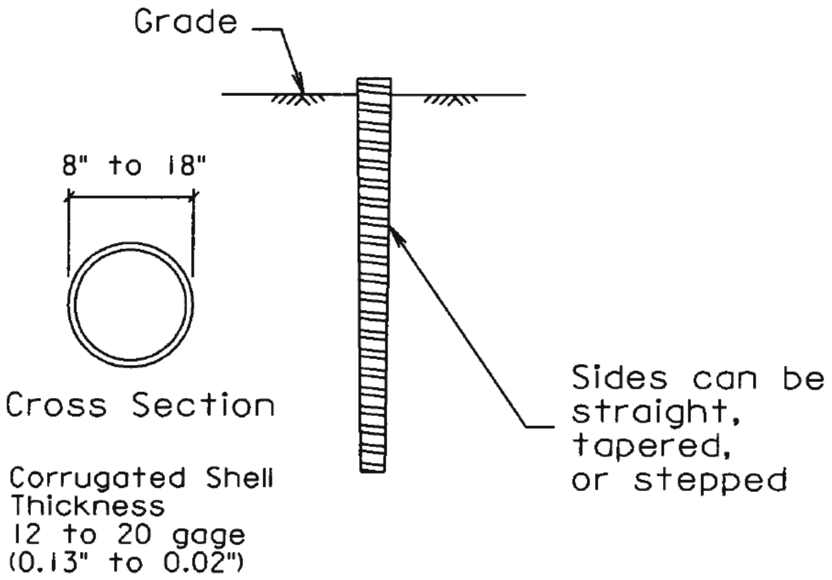

Table modified and reproduced from NAVFAC DM 7.2 (1982)

Table 9 - 2 (con't) SUMMARY OF PILES

Pile Type	Cast-In-Place (CIP) Concrete (Shells driven without a mandrel)
Typical Lengths	15 to 80 ft.
Material Specifications	ACI 318 (for concrete) ASTM A252 (for steel pipe)
Maximum Stresses	See File No. 09.02- 6
Typical Axial Design Loads	55 to 150 tons
Disadvantages	• Difficult to splice after concreting • Considerable displacement
Advantages	• Can be redriven • Shell not easily damaged if fluted
Remarks	• Best suited as friction piles of medium length

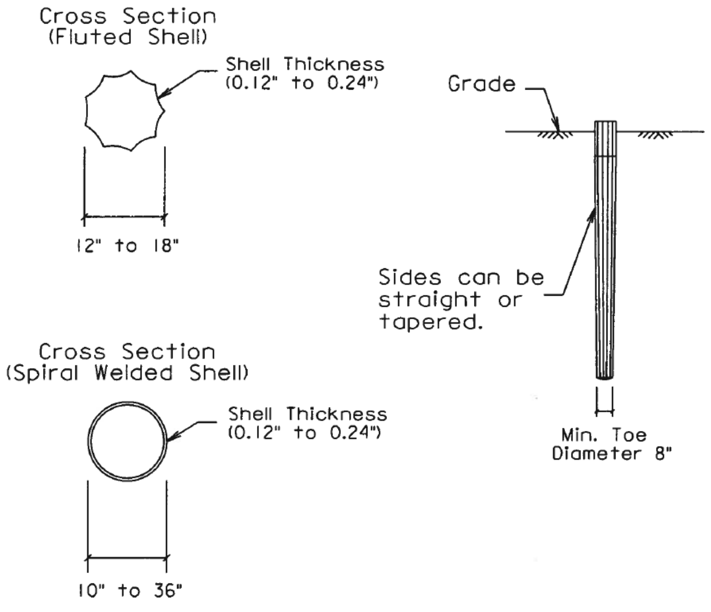

Table modified and reproduced from NAVFAC DM 7.2 (1982)

Table 9 - 2 (con't) SUMMARY OF PILES

Pile Type	Auger-cast piles (aka, "Continuous Flight Auger (CFA) piles" or "Auger-placed, Pressure-injected concrete piles"
Typical Lengths	15 to 50 ft.
Material Specifications	ACI 318 (for concrete) ASTM A82, A615, A722 and A 884 (for reinforcing steel)
Maximum Stresses	Refer to AASHTO
Typical Axial Design Loads	40 to 80 tons
Disadvantages	• Greater dependency on quality workmanship • Not suitable through peat or similar highly compressible material • Requires more extensive subsurface exploration
Advantages	• Economy • Zero displacement • Minimal vibration to endanger adjacent structures • High shaft resistance • Good contact on rock for end-bearing • Convenient for low-headroom underpinning work • Visual inspection of augered material
Remarks	• Best suited as a friction pile in granular material

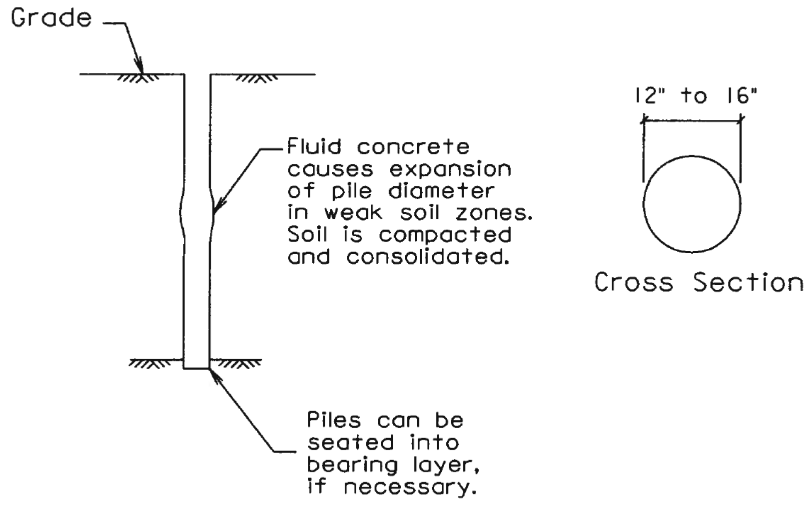

Table modified and reproduced from NAVFAC DM 7.2 (1982)

Table 9 - 2 (con't) SUMMARY OF PILES

Pile Type	Drilled and Grouted Micro-Piles
Typical Lengths	60 to 100 ft.
Material Specifications	ASTM C150 (for Portland cement) ASTM C595 (for blended hydraulic cement) ASTM A615 (for reinforcing steel)
Maximum Stresses	Refer to AASHTO
Typical Axial Design Loads	30 to 100 tons
Disadvantages	• High cost
Advantages	• Low noise and vibrations • Small amount of spoil • Applicable for sites with low headroom and restricted access • Applicable to sites containing rubble and boulders, and karst areas
Remarks	• Can be used for any soil, rock or fill condition.

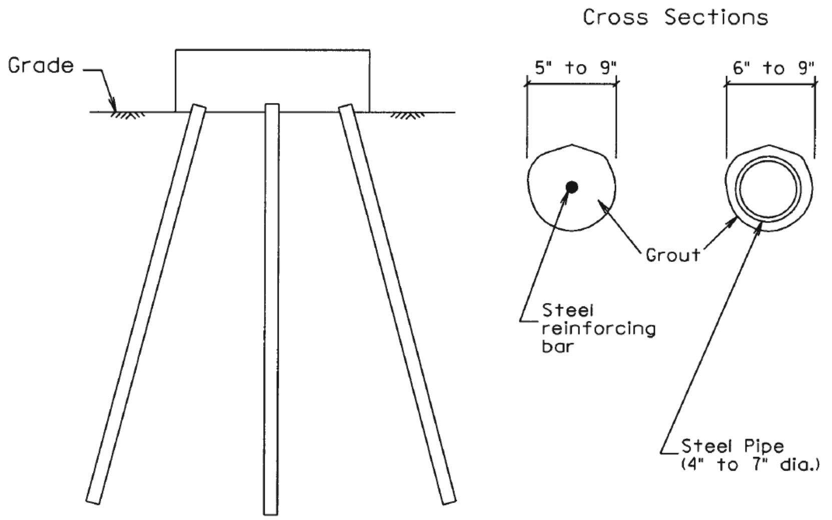

Table modified and reproduced from NAVFAC DM 7.2 (1982)

PILE TYPE SELECTION BASED ON SUBSURFACE AND HYDRAULIC CONDITIONS	
TYPICAL PROBLEM	RECOMMENDATIONS
Boulders overlying bearing stratum	Use heavy nondisplacement pile with a point and include contingent predrilling item in contract.
Loose cohesionless soil	Use tapered pile to develop maximum skin friction.
Negative shaft resistance	Use smooth steel pile to minimize drag adhesion; avoid battered piles. Use bitumen coating or plastic wrap (if feasible) or increase design stress.
Deep soft clay	Use rough concrete piles to increase adhesion and rate of pore water dissipation.
Artesian pressure	Caution required for using mandrel driven thin-wall shells, as generated hydrostatic pressure may cause shell collapse; pile heave common to closed-end pile.
Scour	Do not use tapered piles unless a large part of the taper extends well below scour depth; design permanent pile capacity to mobilize soil resistance below scour depth.
Coarse gravel deposits	Use prestressed concrete piles where hard driving is expected. In coarse soils use of H-piles and open end pipe piles often results in excessive pile lengths.

* Table modified and reproduced (Cheney and Chassie, 1993).

Table 9 - 3

SHAPE CHARACTERISTICS	PILE TYPE	PLACEMENT EFFECT
Displacement	Closed end steel pipe	Increase lateral ground stress.
	Precast concrete	Densifies cohesionless soils, remolds and weakens cohesive soils temporarily. Setup time for large pile groups in sensitive clays may be up to six months.
Nondisplacement	Steel H	Minimal disturbance to soil.
	Open end steel pipe	Not suited for friction piles in coarse granular soils. Piles often have low driving resistances in these deposits making field capacity verification difficult thereby often resulting in excessive pile lengths.
Tapered	Timber Monotubes Thin-wall shells	Increased densification of soil, high capacity for short length in granular soils.

* Table modified and reproduced (Cheney and Chassie, 1993).

Pile Type Selection – Pile Shape Effects

Table 9 - 4