CHAPTER 2

GENERAL CONSIDERATIONS

2-1. General. Many factors must be considered when selecting an appropriate foundation for a hydraulic structure. This chapter presents criteria and methods for selecting the best type of foundation. Information is presented to identify the feasible foundation alternatives for more detailed study. The final selection should be based on an evaluation of engineering feasibility and comparative costs for the potential alternatives considering such factors as safety, reliability, constructability, and life cycle performance. This chapter also presents general criteria for feature design. Such criteria pertain to the type and function of the structure, the nature of the applied loads, and the type of foundation material. The requirements for a subsurface investigation program are also presented.

2-2. Structural and Geotechnical Coordination. A fully coordinated effort from geotechnical and structural engineers and geologists should ensure that the result of the pile foundation analysis is properly integrated into the overall foundation design. This coordination extends through plans and specifications, preconstruction meetings, and construction. Some of the critical aspects of the design process which require coordination are:

a. Preliminary and final selection of pile type.

b. Allowable deflections at the groundline and fixity of the pile head.

c. Preliminary evaluation of geotechnical data and subsurface conditions.

d. Selection of loading conditions, loading effects, potential failure mechanisms, and other related features of the analytical models.

e. Minimum pile spacing and maximum batter.

f. Lateral resistance of soil.

g. Required pile length and axial capacity.

(1) Maximum stresses during handling, driving, and service loading.

(2) Load testing and monitoring programs.

h. Driveability of the pile to the selected capacity.

2-3. Design Considerations. The pile foundation analysis is based upon several simplifying assumptions which affect the accuracy of the results. The computed results must always be reviewed with engineering judgement by the design engineer to assure that the values are reasonable. Also, the analysis results should be compared with load test results.

a. Functional Significance of Structure. The type, purpose, and function of the structure affect decisions regarding subsurface investigation programs, analytical methods, construction procedures and inspection, and performance monitoring. Generally, the proposed structure should be evaluated on the basis of the consequences of failure, that is, the potential for loss of lives and property, economic losses both local and national, compromising the national defense, and adverse public opinion. The designer must be aware of these factors so that a rational approach may be taken throughout the analysis, design, and construction of the project. In order to reduce the potential for failure, as well as to minimize the cost, the designer must apply appropriate factors of safety to the design. These factors of safety are based on the functional significance of the structure, the level of confidence in the foundation parameters, the adequacy of the analysis tools, and the level of construction controls.

b. Definitions of Failure. Structure or foundation failures can be categorized as an actual collapse or a functional failure. Functional failure can be due to excessive deflection, unacceptable differential movements, excessive vibration, and premature deterioration due to environmental factors. For critical structures, failure to meet functional requirements may be as serious as the actual collapse of a lesser structure. Therefore, designers should be cognizant not only of the degree of safety against collapse but also of effects of settlement and vibration on the functional performance.

c. Factors of Safety. Factors of safety represent reserve capacity which a foundation or structure has against collapse for a given set of loads and design conditions. Uncertain design parameters and loads, require a higher factor of safety than required when the design parameters are well known. For most hydraulic structures, designers should have a high level of confidence in the soil and pile parameters and the analysis. Therefore, uncertainty in the analysis and design parameters should be minimized rather than requiring a high factor of safety. For less significant structures, it is permissible to use larger factors of safety if it is not economical to reduce the uncertainty in the analysis and design by performing additional studies, testing, etc. Also, factors of safety must be selected to assure satisfactory performance for service conditions. Failure of critical components to perform as expected can be as detrimental as an actual collapse. Therefore, it is imperative that in choosing a design approach, the designer consider the functional significance of the project, the degree of uncertainty in the design parameters and the analytical approach, and the probability of failure due to both collapse and functional inadequacy.

d. Soil-Structure Considerations for Analysis. The functional significance and economic considerations of the structure will determine the type and degree of the foundation exploration and testing program, the pile test program, the settlement and seepage analyses, and the analytical models for the pile and structure. For critical structures the foundation testing program should clearly define the necessary parameters for the design of the pile foundation, such as soil types and profiles, soil strengths, etc. (Paragraphs 3-1 and 3-2 give further details.) Although pile load tests are usually expensive and time consuming, they are invaluable for confirming or modifying a pile foundation design during the construction phase. A well-planned and monitored pile load test program will usually save money by allowing the designer to utilize a lower factor of safety or by modifying the required number or length of piles required. A pile load test program should be considered for all large structures for which a pile foundation is required. (Paragraph 3-6 gives further details.) Depending upon the type of foundation material, the nature of the loading, the location of the ground water, and the functional requirements of the structure, a detailed seepage analysis and/or pile settlement analysis may also be required to define adequately the pile-soil load transfer mechanism and the resulting parameters necessary for an adequate pile design. Where differential movement between monoliths is a concern, an accurate estimate of pile settlement may be crucial, particularly if the monoliths have significantly different load levels. (Paragraphs 3-4 and 4-4 give further discussions.) Decisions regarding the type and sophistication of the analytical models for the pile and the structure should also be made with the functional significance of the structure in mind. For example, it may be satisfactory to analyze the pile foundation for a small, lightly loaded structure based on conservative assumptions for pile parameters and a crude structural model; however, a larger, more important structure would probably require a detailed single pile analysis to establish the proper pile parameters. Perhaps it would even be necessary to use a structural model capable of considering the actual structural stiffness to insure correct load distribution to the piles. (See paragraph 4-5 for further discussion.)

e. Construction and Service Considerations. No matter how thorough and well researched a design may be, it is only as good as its execution in the field. The proof of the entire design and construction process is in the performance of the final product under service conditions. Therefore, the designer should consider the analysis and design of a structure and its foundation as parts of an engineering process that culminates with the successful long-term performance of the structure for its intended purposes. The designer prepares the specifications and instructions for field personnel to assure the proper execution of the design. The designer must discuss critical aspects of the design with construction personnel to make sure that there is a thorough understanding of important design features. For critical structures a representative of the design office should be present in the field on a continuous basis. One such example would be a major pile test program where the execution of the pile test and the gathering of data is critical for both a successful testing program and verification of design assumptions. Another critical activity that requires close cooperation between the field and the designer is the installation of the foundation piling. The designer should be involved in this phase to the extent necessary to be confident that the design is being properly executed in the field. As a general principle, designers should make frequent visits to the construction site not only to ensure that the design intent is being fulfilled but also to familiarize themselves with construction procedures and problems to improve on future designs and complete as-built records. Once the project is in operation, the designer should obtain feedback on how well the structure is fulfilling its operational purposes. This may require that instrumentation be a part of the design or may take the form of feedback from operating personnel and periodic inspections.

2-4. Nature of Loadings.

a. Usual. Usual loads refer to conditions which are related to the primary function of a structure and can be reasonably expected to occur during the economic service life. The loading effects may be of either a long term, constant or an intermittent, repetitive nature. Pile allowable loads and stresses should include a conservative safety factor for such conditions. The pile foundation layout should be designed to be most efficient for these loads.

b. Unusual. Unusual loads refer to construction, operation or maintenance conditions which are of relatively short duration or infrequent occurrence. Risks associated with injuries or property losses can be reliably controlled by specifying the sequence or duration of activities, and/or by monitoring performance. Only minor cosmetic damage to the structure may occur during these conditions. Lower factors of safety may be used for such loadings, or overstress factors may be applied to the allowables for these loads. A less efficient pile layout is acceptable for these conditions.

c. Extreme. Extreme loads refer to events which are highly improbable and can be regarded as emergency conditions. Such events may be associated with major accidents involving impacts or explosions and natural disasters due to earthquakes or hurricanes which have a frequency of occurrence that greatly exceeds the economic service life of the structure. Extreme loadings may also result from a combination of unusual loading effects. The basic design concept for normal loading conditions should be efficiently adapted to accommodate extreme loading effects without experiencing a catastrophic failure. Extreme loadings may cause significant structural damage which partially impairs the operational functions and requires major rehabilitation or replacement of the structure. The behavior of pile foundations during extreme seismic events is a phenomenon which is not fully understood at present. The existing general approach is to investigate the effects of earthquake loading at sites in seismic Zones 1 or 2 by applying psuedostatic forces to the structure and using appropriate subgrade parameters. In Zones 3 or 4 a dynamic analysis of the pile group is appropriate. Selection of minimum safety factors for extreme seismic events must be consistent with the seismologic technique used to estimate the earthquake magnitude. Designing for pile ductility in high risk seismic regions is very important because it is very difficult to assess pile damage after earthquakes and the potential repair costs are very large. Effects related to liquefaction of subsurface strata are discussed in paragraph 3-5.

2-5. Foundation Material.

a. Known Data. After a general site for a project is selected, the designer should make a site visit to examine the topography at the site. Rock outcrops or highway cuts on or near the site may provide valuable information of the subsurface conditions. An examination of existing structures in the vicinity may also provide information. A visit to the local building department may provide foundation information and boring logs for nearby buildings. The highway department may have soil and geological information in the area for existing roads and bridges. Valuable soil and geological information can be obtained from other governmental agencies, such as the United States Geological Survey (USGS), Soil Conservation Service (SCS), Bureau of Records, etc., for even remotely located areas. Colleagues may be able to provide information on projects they have worked on in the area. Check the files for previous jobs your office might have built or explored in the area.

b. Similar Sites. It is important to determine the geological history of the site and geological origins of the material that exists at the site. The geological history of the site will provide information on the properties of the different geological zones and may allow the designer to find sites with similar geological origins where data are available on the soil and rock properties and on pile behavior.

c. Exploration Requirements. The designer must lay out an exploration and testing program that will identify the various material zones and their properties. This exploration and testing program shall identify the various soil and rock layers at the site; the groundwater table, water quality, and existing aquifers; and information relating to faults at the site. The above information should be obtained to the degree that is necessary to design an adequate foundation for the proposed structure.

2-6. Identification and Evaluation of Pile Alternatives.

a. General. Structures may be founded on rock, on strong or weak soils, cohesive or noncohesive soils, above ground level, below water level, etc. The type of foundation used to support a structure depends on local conditions. After obtaining a general evaluation of the subsurface conditions the engineer should attempt to identify all potential useful foundation alternatives for a structure. Three basic types of foundations are available: soil-founded, various types of piles, and piers or caissons. Each of these foundation types has many subcategories. The following paragraphs provide a short description and evaluation of the various pile types.

b. Piles. The purpose of a pile foundation is to transfer and distribute load through a material or stratum with inadequate bearing, sliding or uplift capacity to a firmer stratum that is capable of supporting the load without detrimental displacement. A wide range of pile types is available for applications with various soil types and structural requirements. A short description of features of common types of piles follows:

(1) Steel H-Piles. Steel H-piles have significant advantages over other types of piles. They can provide high axial working capacity, exceeding 400 kips. They may be obtained in a wide variety of sizes and lengths and may be easily handled, spliced, and cut off. H-piles displace little soil and are fairly easy to drive. They can penetrate obstacles better than most piles, with less damage to the pile from the obstacle or from hard driving. The major disadvantages of steel H-piles are the high material costs for steel and possible long delivery time for mill orders. H-piles may also be subject to excessive corrosion in certain environments unless preventive measures are used. Pile shoes are required when driving in dense sand strata, gravel strata, cobble-boulder zones, and when driving piles to refusal on a hard layer of bedrock.

(2) Steel Pipe Piles. Steel pipe piles may be driven open- or closed-end and may be filled with concrete or left unfilled. Concrete filled pipe piles may provide very high load capacity, over 1,000 kips in some cases. Installation of pipe piles is more difficult than H-piles because closed-end piles displace more soil, and open-ended pipe piles tend to form a soil plug at the bottom and act like a closed-end pile. Handling, splicing, and cutting are easy. Pipe piles have disadvantages similar to H-piles (i.e., high steel costs, long delivery time, and potential corrosion problems).

(3) Precast Concrete. Precast concrete piles are usually prestressed to withstand driving and handling stresses. Axial load capacity may reach 500 kips or more. They have high load capacity as friction piles in sand or where tip bearing on soil is important. Concrete piles are usually durable and corrosion resistant and are often used where the pile must extend above ground. However, in some salt water applications durability is also a problem

with precast concrete piles. Handling of long piles and driving of precast concrete piles are more difficult than for steel piles. For prestressed piles, when the required length is not known precisely, cutting is much more critical, and splicing is more difficult when needed to transfer tensile and lateral forces from the pile head to the base slab.

(4) Cast-in-Place Concrete. Cast-in-place concrete piles are shafts of concrete cast in thin shell pipes, top driven in the soil, and usually closed end. Such piles can provide up to a 200-kip capacity. The chief advantage over precast piles is the ease of changing lengths by cutting or splicing the shell. The material cost of cast-in-place piles is relatively low. They are not feasible when driving through hard soils or rock.

(5) Mandrel-Driven Piles. Mandrel-driven piles are thin steel shells driven in the ground with a mandrel and then filled with concrete. Such piles can provide up to a 200-kip capacity. The disadvantages are that such piles usually require patented, franchised systems for installation and installation is not as simple as for steel or precast concrete piles. They offer the advantage of lesser steel costs since thinner material can be used than is the case for top-driven piles. The heavy mandrel makes high capacities possible. Mandrel-driven piles may be very difficult to increase in length since the maximum pile length that can be driven is limited by the length of the mandrel available at the site. Contractors may claim extra costs if required to bring a longer mandrel to the site.

(6) Timber. Timber piles are relatively inexpensive, short, low-capacity piles. Long Douglas Fir piles are available but they will be more expensive. They may be desirable in some applications such as particular types of corrosive groundwater. Loads are usually limited to 70 kips. The piles are very convenient for handling. Untreated timber piles are highly susceptible to decay, insects, and borers in certain environments. They are easily damaged during hard driving and are inconvenient to splice.

c. Evaluation of Pile Types.

(1) Load Capacity and Pile Spacing. Of prime importance is the load-carrying capacity of the piles. In determining the capacity of a pile foundation, it is important to consider the pile spacing along with the capacity of individual piles. The lateral load resistance of the piles may also be important since lateral loads can induce high bending stresses in a pile.

(2) Constructability. The influence of anticipated subsurface and surface effects on constructability must be considered. Piles susceptible to damage during hard driving are less likely to penetrate hard strata or gravel and boulder zones. Soil disturbance or transmission of driving vibrations during construction may damage adjacent piles or structures. Pile spacing and batters must be selected to prevent interference with other structural components during driving. The ease of cutting or splicing a pile may also affect constructability.

(3) Performance. The pile foundation must perform as designed for the life of the structure. Performance can be described in terms of structural displacements which may be just as harmful to a structure as an actual pile failure. The load capacity should not degrade over time due to deterioration of the pile material.

(4) Availability. Piles must be available in the lengths required, or they must be spliced or cut off. Project scheduling may make lead time an important consideration, since some piles may require up to 6 months between order and delivery.

(5) Cost. Once a pile type satisfies all other criteria, relative cost becomes a major consideration. For comparisons between types of piles, it may be adequate to compare the pile cost per load capacity. For example, an installed H-pile may cost $40 per linear foot and have a capacity of 200 kips for a 50-foot length. The unit capacity cost would then be $10 per kip. A comparison between unit capacity costs may lead to an obvious exclusion of certain pile types. The cost evaluation should include all expenses related to and dependent on the pile foundation. Such costs may include additional expense for storage or splicing. They may include pressure-relief systems used to reduce uplift pressures and thus control pile loads. In addition, any required modifications to the structure to accommodate the piles should be included in a comparative cost estimate. For example, an increase in base slab thickness may be required to provide additional embedment for the tops of the piles.

d. Preliminary Evaluations. All identified foundation alternatives should first be evaluated for suitability for the intended application and cost. For piles, this evaluation should be based on the capacity, availability, constructability, and expected performance of the various types of piles. Initial evaluation of nonpile alternatives should be based on similar criteria. This will limit further studies to those foundation alternatives which are reasonably feasible. During this initial evaluation, it may also be possible to eliminate from consideration obvious high-cost alternatives.

e. Final Evaluations. The final evaluation and selection should be based mainly on relative costs of the remaining alternatives. This evaluation should include the costs of structural or site modifications required to accommodate the foundation type. Cost and other factors may be important in the selection. Differences in delivery or installation schedules, levels of reliability of performance, and potential construction complications may be considered. When comparing a pile foundation to another type of foundation, it will be necessary to develop a preliminary pile layout to determine a reasonable estimate of quantities.

2-7. Field Responsibilities for the Design Engineer.

a. Loading Test. On all major structures with significant foundation costs, pile load tests are required. On minor structures, pile load tests may not be required depending on economics, the complexity of the soil conditions, the loading conditions and the experience the designer has with pile foundations in that area. Load tests of piles should be performed to finalize pile lengths and to provide information for improving design procedures. Load tests are performed prior to construction of the pile foundation. Consideration should be given to the use of indicator pile tests, that is the capacity may be inferred using the pile driving analyzer or other similar technique. These are powerful tools that can augment but not replace static tests.

b. Field Visits. The quality design of a pile foundation design is only as good as the as-built conditions. In order to ensure correct installation of the pile foundation, it is important for the design engineer to visit the construction site frequently. Field visits should be made to view critical construction phases and to discuss progress and potential changes in procedures with the construction representative. Critical items include monitoring and maintaining detailed records of driving operations, especially:

(1) Driving reports for individual piles - date and times, placement position and alinement; blow counts, difficulties and interruptions during driving; installation and location of any pile splices.

(2) General driving data - complete descriptions of driving equipment, adjustments and changes (leads, hammer, anvil, cap, cushions, etc.); pile storage and handling procedures; pile interference; pile heave.

(3) Driving restrictions - existing structures in vicinity; driving near new concrete; limiting water elevation.

c. Instructions to the Field. Instructions to the field are necessary to convey to field personnel the intent of the design. Instructions to the field should be conveyed to the field by the designers through a report, "Engineering Considerations and Instructions for Field Personnel" as required by EM 1110-2-1910. This report should include the following information to the field:

(1) Present the design assumptions made regarding interpretation of subsurface investigation data and field conditions.

(2) The concepts, assumptions, and special details of the design.

(3) Assistance to field personnel in interpreting the plans and specifications.

(4) Information to make field personnel aware of critical areas in the design which require additional control and inspection.

(5) Provide results of wave equation analysis with explanation of application of results to monitor driving operations.

(6) Provide guidance for use of pile driving analyzer to monitor driving operations.

2-8. Subsurface Conditions. The ultimate axial load capacity of a single pile is generally accepted to be the total skin friction force between the soil and the pile plus the tip capacity of the pile, which are dependent on the subsurface conditions. The ultimate axial capacity of individual friction piles depends primarily upon the type of soil: soft clay, stiff clay, sand, or stratified soil layers. In soil deposits that contain layers of varying stiffness, the ultimate axial pile capacity cannot be equal to the sum of the peak strength of all the materials in contact with the pile because the peak strengths are not reached simultaneously. Failure is likely to be progressive. The existence of boulders or cobbles within foundation layers can present driving problems and hinder determination of ultimate axial capacity of a single pile.

2-9. Pile Instrumentation. Pile instrumentation can be delineated into three categories: instrumentation used during pile load tests to obtain design data, pile driving analyzer used to control quality of pile installation, and permanent instrumentation used to gather information during the service life of the project. Decisions on the type of instrumentation for pile load tests must be an integral part of the design. The designer should select instrumentation that has sufficient accuracy to measure the required data. Permanent instrumentation is used to gather data relating to the state of stress and behavior of the pile under service load conditions. Useful knowledge can be gained from permanent instrumentation, not only about the behavior of a particular pile foundation, but also about analysis and design assumptions in general. Verification (or modification) can be obtained for analytically derived information such as pile settlement, pile head fixity, location of maximum moment within the pile, and the distribution of loads to an individual pile within a group. However, a permanent instrumentation program can be very expensive and should be considered only on critical projects. Also, effective use of the instrumentation program depends on a continuing commitment to gather, reduce, and evaluate the data.