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Monitoring of Driven Pile Installation

PDH Credits:

2 PDH

Course No.:

MDP101

Publication Source:

US Corp of Engineers

"Pile Driving Equipment – Ch. 4 – Monitoring of Pile Installation"
Pub. # TI 818-03
(supersedes COE Pub. EI-02G001
Note: Ch.4 remained unchanged)

Release Date:
Aug. 1998

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CHAPTER 4

MONITORING OF PILE INSTALLATION

4-1. EQUIPMENT OPERATION. Successful pile driving is dependent upon both the condition of the equipment and the operating technique used. Failure to observe the proper procedures with the equipment can result in loss of energy imparted to the pile, failure to reach the desired penetration depth, property damage, personal injury, and equipment breakdowns, which lead to downtime, job delays, and contract disputes.

a. Condition of Equipment. Equipment should be maintained and operated in accordance with manufacturer's recommendations. This includes proper preparation of the equipment, correct setup before driving, good operation during driving, and proper transport and storage procedures.

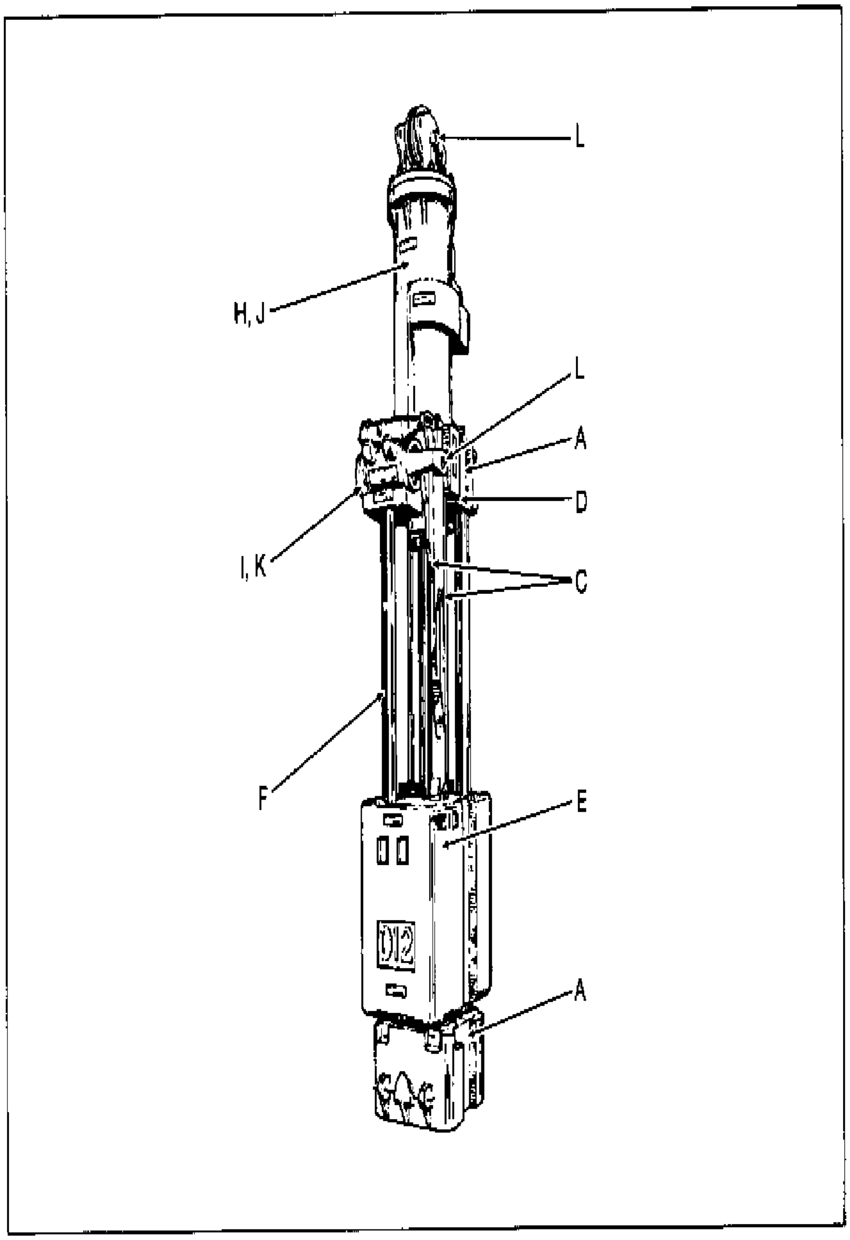
(1) Hammer. The hammer is the element that directly interfaces with the pile. Thus, it transmits and receives the most vibration and impact during driving. Although most pile drivers in use today are relatively simple machines, attention to their basic maintenance is still important. It is also essential that this equipment, in common with most construction equipment, must be operated by personnel with the proper training and experience in the use of the equipment.

(a) Impact Hammers. The most important element in the efficient operation of impact hammers is proper lubrication. All wear surfaces must be kept lubricated by the means provided for either on the machine or from the outside. Typical lubrication points for an air/steam hammer are shown in figure 4-1. Diesel hammers vary widely in their lubrication systems, but the entire cylinder assembly must be lubricated in its full length, whether by grease or oil. Hydraulic impact hammers are similar to air/steam hammers except for the hydraulic system and cylinder(s). In these cases, their maintenance is more like that of a vibratory hammer (see next section). Also, due to the high loads during ram deceleration and pile rebound, impact hammers are subject to dynamic stresses. All fasteners must be kept tight, and parts which are worn, cracked, or broken must be replaced.

(b) Vibratory Hammers. A chart of basic items to watch for with vibratory hammers is shown in table 4-1.

(2) Driving Cap. The driving cap transmits the impact force from the hammer to the pile. Its proper setup and maintenance are central to successful pile driving.

(a) Cushion. Both hammer and pile cushion material should be configured and installed so that there is adequate cushioning for the ram and the pile. Materials which are too hard, or less than complete cushion stacks must be avoided; cushions which are added piece by piece during driving must also be avoided. Cushion material is an expandable item; it degenerates during its life with heat and plastic deformation; it is essential that it is replaced when it is burnt or deformed to its compressive limit. Cushion whose stack height is 75 percent of the original, uncompressed height should be replaced. Also, when piling are designed using the wave equation analysis, it is essential that the cushion configuration assumed during the wave equation analysis be a realistic one in the field and that the configuration assumed during the analysis be replicated in the field. This is especially important with a concrete pile cushion; inadequate cushion may lead to tension cracking during driving and excessive material may lead to unanticipated energy losses. If the pile cushion is plywood and the pile concrete, a new pile cushion should be used with every pile.



Lubrication Points: (a) Jaws
(b)Trip Faces
(c) Slide Bar
(d) Slide Bar Dovetail
(e & f) Columns
(g-j) Air or Steam Ports

Figure 4-1. Lubrication points, air/steam hammer.

Table 4-1. Do’s and do not’s of VIbratory Hammers.

Things that Always Need to be Done	Things that Never Need to be Done
Always store oily rags in containers. If these get into a hydraulic system, there can be problems.	Never allow unauthorized or unqualified people to operate, maintain, or come within 30 meters of the equipment.
Always remove all tools from unit before starting.	Never allow anyone to stand directly under or within at least 3 meters of the hammer or pile being driven during operation. Failure to do so could result in injury or death caused by falling parts, rocks, or dirt on the hammer.
Always be sure that, with hydraulic systems, all pressure is out of the system and that all pressure gauges read zero before working on the hydraulics of the system. The high pressure fluid in hydraulic lines can be very dangerous if released.	Never operate the power pack’s engine in a in a closed area. The breathing of the fumes can be fatal.
Always make sure that all hose hittings or connections are very tight when reassembled. Failure to do so can result in the hoses coming loose, flying around, hydraulic fluid spraying everywhere, and injury or death.	Never smoke or use an open flame when servicing batteries. Proper ventilation is necessary when charging batteries. On units with a power pack enclosure, all of the doors of the unit must be open during battery charging.
Always make sure that electrical systems are properly grounded during operation. Also, make sure that they are not connected to any power source in anyway and that there is no voltage of any kind in the system before servicing same.	Never smoke when filling fuel tank or hydraulic reservoir or, for that matter while anywhere near exciter, hoses, or power pack. Diesel fuel, gasoline, and hydraulic fluid are all very flammable.
Always make sure that electrical connections and wiring are tight and completely insulated to prevent shock if accidentally touched. This is especially important in waterfront or marine situations; uninsulated wire can result in electrocution.	Never adjust or repair the unit while it is in operation, except with the main motor and clamp controls provided for that purpose. If you need to make any other adjustments, shut the entire system down first.
Always be sure to wear gloves and protective clothing while working on any part of the system. It is even better to wait until the system has cooled down. Hydraulic components, electrical wiring and switchgear, and the engine get very hot during operation.	Never store flammable liquids near the engine.
Always make sure that the pile is firmly gripped by the jaws when clamping.	Never unclamp the exciter from the pile when there is any line pull on the suspension or when the hammer is still vibrating.

(b) Anvils and Helmets. Anvils and helmets must be of a construction that will withstand the high loads and stresses of impact pile driving. They should be inspected thoroughly before use. Any helmet or anvil that has any cracks, broken pieces, or thin wall sections that might break in use should be rejected before driving begins. During use, a cap should be inspected frequently for developing cracks or broken or missing pieces, and removed from the job if any of these is discovered during inspection.

(c) Mandrel. Mandrels also transmit high loads. They should be inspected during use for any cracks or other mechanical failures, and these should be repaired before driving is resumed.

b. Hammer Operation. There are several important performance parameters to monitor during driving.

(1) Hammer Stroke. The single most important parameter to look for is the stroke of the ram.

(a) Single Acting Hammers. With single acting hammers of any kind, the only source of energy for the ram on the downstroke is its drop through the gravity field. So it is absolutely essential that its stroke be what is required by the piling being driven, whether that be full or partial stroke. This stroke should be achieved when the pile is at refusal; some hammers (especially diesel hammers) cannot achieve full stroke without the pile energy rebound of refusal driving.

(b) Other Impact Hammers. Although the stroke is not as important with hammers that have assistance on the downstroke, it is important to establish what stroke is required for the particular job.

(c) Monitoring of Stroke. If the ram is visible from the outside of the hammer, then visual monitoring of the stroke is possible. With air/steam hammers, as the ram moves it wipes most of the lubricant off of the columns. The length of this wiped area will determine the stroke of the hammer. With open-end diesel hammers, a striped pole can be mounted on top of the hammer. As the ram raises up, the stroke can be determined by comparing the maximum height of the ram with the highest point of the ram raising.

(2) Speed. Although the hammer speed is a general indicator of the performance of the hammer, except for single-acting diesel hammers, it cannot be used to determine the energy output of the hammers. This is because there are simply too many variables influencing the motion of the ram, especially the variations in energy rebound from the pile. With single-acting diesel hammers, devices exist that can estimate the energy of the hammer based on its blow rate.

(3) Pressure. With external combustion hammers, the pressure of the operating fluid is important in the energy output of the hammers. With single-acting hammers, although no direct correlation can be made between pressure and output energy, monitoring the pressure can be a useful tool in diagnosing problems with the driving system. For other hammers, fluid pressure of the motive fluid or trapped dashpot air is part of the downstroke assistance and is an important factor in hammer energy. For proper readings, any pressure readings should be taken at the hammer by a pressure gauge at the hammer or by remote sensor.

(4) Direct Energy Monitoring. If the ram is not visible, or for more complete information on the energy output of the hammer, devices exist that can determine the energy output of the hammer, either from the hammer itself or after the stress wave has passed through the cushion material and drive cap. These can be either obtained from the manufacturer or third-party vendors and consultants. It is very important that these devices be properly installed, calibrated, and operated by experienced and trained personnel who are very familiar with their use; incorrect installation, calibration, or operation can result in erroneous readings. Complete reports on the use of these devices should be required if they are used.

4-2. PILE INSTALLATION. Installation of the production piles, those piles that are intended to support the structure under construction, will be monitored and records kept to provide data to assess the capacity and quality of the pile foundation.

a. Pile Driving Records. A complete pile driving record will be prepared for each pile driven to its embedment depth. These records provide important data concerning the nature of the soils that are penetrated, provide evidence of any soil disturbance that is a result of driving, and indicate the penetration resistance. The penetration resistance, pile driving analyzer data recorded during driving of indicator and some of the production piles, and recorded later during restrikes, can be analyzed to assess the driving stresses, capacity, and quality of the pile.

(1) Impact Hammers. The make, model, energy, stroke, pile, and hammer cushions should all be recorded on the header portion of the record. The remaining portion of the pile driving record is used to record the penetration resistance (blows applied to the pile within a unit distance such as 1 foot.

(a) A wave equation analysis should be performed if blow counts that are recorded are not similar to those observed during driving and restrike of the indicator piles at the start or prior to construction.

(b) The blow counts should be plotted as a function of depth to determine depths where the soil may be strongest and to indicate if the pile had been driven to the proper embedment depth and bearing stratum.

(c) The average blow count should be computed for each pile and the average of each pile plotted versus time. This plot will indicate if the penetration resistance is changing as additional piles are installed. Increases in the penetration resistance with time may indicate that the soil is getting stronger, perhaps from densification of the soil as a result of driving. Increasing penetration resistance with time may also indicate a temporary drop in pore water pressure as a result of the disturbance of dense sands or stiff clays. Decreases in the penetration resistance with time may indicate driving into weaker soil or perhaps the temporary buildup of excess pore pressures if the soils are loose and fine grained with low permeability.

(d) Abrupt changes in penetration resistance will be investigated to determine the cause. Abrupt changes can indicate a variety of problems that will cause the pile to be rejected. The pile should be replaced if driving damaged the pile. The installation equipment may have to be changed to install a different type of pile and pile length.

(2) Vibratory Drivers. The make, model, weight, dynamic force, frequency or range of frequencies, maximum eccentric moment, and clamping method will be recorded on the form. The remaining portion of the form will be used to record the depth, the time to reach a given depth, and the frequency to reach the depth.

(a) The ultimate piling capacity cannot yet be determined from vibratory driver records. An impact hammer is required to drive the pile to the embedment depth.

(b) A static load test is typically required to verify that vibratory driven piles have adequate pile capacity. Specifications should require a static load test for each type of pile and soil.

(c) Steel H-piles and pipe piles can be easily clamped to a vibratory driver. Concrete and timber piles may require bolts to secure the vibratory driver.

(d) The vibratory driver is nearly always the most efficient tool for extracting a pile and should be used for steel, wood, or concrete. The vibratory driver first breaks the pile loose from the soil and then extracts the pile. A line attached directly to the pile can aid extraction when the pile is too heavy for the driver.

(e) The dynamic force must be sufficient to maintain an adequate amplitude to continue penetration of the soil. This is especially important if the soil is clay. Driving is still possible if the driver is sufficiently large. A rule of thumb for vibratory drivers is a small driver for piles up to 30 feet, medium driver for piles up to 50 feet, and a larger driver for piles over 50 feet in length.

b. Pile Driving Analyzer. The PDA is recommended during pile installation or during some part of the pile installation operation to calibrate wave equation analysis and to evaluate the quality of the driven pile. Calibration of wave equation analysis increases reliability of the bearing graph and driving stresses calculated by wave equation analysis.

(1) PDA analysis will be performed at the start of any significant project and later during pile installation.

(a) The number of static load tests can be reduced to just one or two when PDA is performed. More static load tests are required for variable or erratic soils.

(b) The PDA can be expected to provide good estimates of pile capacity in uncemented sands.

(c) The PDA can provide good estimates of pile capacity in silts or clays, but careful analysis is required because of high damping forces.

(2) The pile is expected to have sufficient capacity if the bearing graph calculated by wave equation analysis indicates an ultimate bearing capacity of at least twice the design load for the measured penetration resistance at the embedment depth.

(a) Sample production piles will be tested by PDA to ensure that the pile foundation will have sufficient capacity.

(b) PDA will be performed if the pile driving record indicates a significant reduction in pile capacity so that there is doubt that the piles can adequately support the structure.

(3) Results of the PDA and wave equation analysis performed by the PDA technician should indicate the load-displacement behavior of the pile and provide a value of the pile settlement at the design load.

(a) The settlement for the design load should usually be less than 0.5 inch.

(b) Calculation of load-displacement behavior with PDA equipment requires calibration with a static load test.

(4) Observation of the wave forms on the oscilloscope of the PDA equipment by the PDA technician will be performed to indicate the quality of the pile and to determine if any damage occurred to the pile as a result of driving.

(a) The PDA data will tell if there is any probable damage to the pile top.

(b) The PDA will show the effect of changes in the helmet, cushions, or stresses induced at the pile top.

(5) PDA data will permit analysis of hammer performance.

(a) The analysis can show the effect of reduced throttle settings or steam pressure.

(b) The analysis can calculate the maximum energy actually transmitted to the pile. This energy should be compared with the rated hammer energy to determine the efficiency of the hammer assembly. Low efficiencies indicate problems in the driving system and that maintenance is required.

(c) The analysis can assist in determining where the energy losses are occurring in the driving system.

c. Restrikes. Restrikes are useful for determining effects of soil freeze or relaxation and to evaluate long-term pile capacity. Restrikes of previously driven piles should be accomplished using a swinging leader to minimize time required for positioning the rig and pile driving system.

(1) Restrikes are recommended during installation of the production piles if restrikes performed prior to or at the start of pile installation indicated more than 25-percent change in the penetration resistance after a delay exceeding 16 hours.

(2) Restrikes are required when pile driving records indicate significant changes in penetration resistance, i.e., > 25 percent compared to those piles driven earlier.

(3) Restrikes are required when pile driving records indicate penetration resistances that are not compatible with adequate pile capacity.

4-3. PREVENTION OF PILE DAMAGE DURING DRIVING. Damage can be prevented by eliminating overstressing (overdriving) of the pile. Overstressing occurs when driving stresses exceed the allowable limits.

a. Pile Damage. Overstressing is frequently attributed to using a hammer too large for the pile being driven, misalignment of the pile and hammer, material failure within the drive cap such as loss or insufficient cushion, or malfunction of the equipment.

(1) General Indicators of Damage. The pile is probably damaged if any of the indicators given in table 4-2a are observed.

(a) Hollow piles that can be inspected after driving may show overdriving from crushing or distortion of the pile material.

(b) Any piles suspected of being damaged will be promptly evaluated to determine its effect on the overall foundation design.

(c) Repetitive damage to piles may require modification of the installation equipment or installation method.

(2) Specific Indicators of Damage. Table 4-2b illustrates types of damages observed in timber, concrete, and steel pile.

Table 4-2. Indicators of pile damage.

Observation	Pile Damage
General Indicators of Damage	
A sudden increase, decrease, or irregular penetration resistance	Pile breakage if the soil formation has not changed from that when previous piles had been driven.
Drifting of the pile off location as observed at the ground surface.	Pile breakage.
A sudden lateral snap of the pile head.	Pile breakage from bending.
Damage observed at the head.	Similar damage may occur at the tip.
Two or more cycles of decreasing and increasing penetration resistance.	Progressive crushing of the tip.
Vibration and/or noise of Previously driven piles.	Interference with the pile being driven.
Types of Observed Damage	
Type of Pile	Damage
Timber	Brooming at the tip or head, splintering, or breaks.
Concrete	Spalling, transverse cracks
Steel	Bending, reduction in cross-section.

b. Prevention of Damage. Overstressing the pile can be prevented by determining how much driving the pile can tolerate. This is accomplished by completing a wave equation analysis to determine driving stresses. These stresses and corresponding penetration resistances will be avoided during pile installation. Experience on how hard the pile can be driven in the field without damage can also assist in avoiding damage.

(1) Wave Equation Analysis. The wave equation analysis calculates driving stresses which, when compared with allowable stresses, can determine when overstressing will occur for the selected pile driving system and the pile.

(a) A preliminary wave equation analysis should be made as part of the foundation design procedure to estimate driving stresses for the selected pile foundation, pile driving system, and cushions. The pile can be expected to be overstressed and to be damaged if the driving energy of the selected hammer is exceeded or thickness of pile cushions is reduced.

(b) Wave equation analysis will be performed as part of driving indicator piles with the PDA. Results of this analysis will confirm the selection of the pile driving system and provide guidance on the limits of the driving energy to be sure that driving stresses will be less than the allowable stresses.

(2) Good Driving Practice. All driven piles are subject to driving limitations.

(a) The piles will be properly aligned with the pile hammer and driving energy limited to maintain driving stresses within allowable limits.

(b) Cushions will be maintained at the thickness determined from results of driving of indicator piles with the PDA.

(c) Timber piles are especially vulnerable to brooming and splitting near the pile top or tip when driven. Driving should stop immediately when hard driving is encountered as indicated by a sudden increase in the penetration resistance or if the pile is observed to drift off location. A vibratory driver can be substituted for an impact hammer to eliminate damage from hard driving.

(d) The driveability of concrete piles is often limited by the tensile strength of the pile, especially long prestressed concrete piles. Concrete piles should be driven initially with low energy that is about 50 percent of the maximum energy to be applied to the pile. The maximum driving energy is applied when the pile is nearly at the embedment depth. This guidance therefore requires that concrete piles should be driven with hammers of variable energy to safeguard the integrity of the pile.

(e) Steel piles, especially open-end pipe and H-piles, are capable of hard driving. Pile tips may be protected with driving shoes, but prolonged hard driving should be avoided.

(f) Piles suspected of being damaged should be extracted and replaced. Vibratory drivers are efficient extractors of piles if the pile can be clamped to the driver.

(g) Pile driving should cease immediately when sudden increases in penetration resistance are observed to avoid overdriving. Timber piles are especially vulnerable to brooming or splitting at the top or tip of the pile when hard driving occurs. Prolonged hard driving will be avoided.

(3) Restrike of Selected Piles. Selected piles will be restruck with PDA equipment to measure the quality of the driven piles and to assess pile capacity.

(a) Piles that should be restruck include those that have some sign of possible malfunction, but not judged serious enough to extract. Examples include penetration resistance that is not as high as expected and where the pile capacity is in doubt, unexplained changes in penetration resistance, penetration resistance not as high as previously driven piles, and piles with some damage at the pile head.

(b) Driving stresses evaluated by the analysis during restrike will not exceed the yield or ultimate strength of the pile material. This provides a slight margin of safety against damage because the duration of the peak of the driving stresses is short.

(c) The quality of restruck piles will be evaluated by the PDA technician and made a part of the quality assurance record.

4-4. COMPLICATIONS. Driving of the production piles may lead to complications that could compromise the capacity of the foundation and interfere with the operation of adjacent structures. These complications can be caused by penetration resistances that are either too low or too high when driven to the embedment depth, by ground movement, and by environmental problems. Refer to paragraph 4-3 for solution to problems with pile integrity.

a. Problems with Low Resistance. The pile foundation will not have sufficient capacity if the penetration resistances are too low. Abrupt unexpected reductions in the penetration resistance may indicate a damage pile. Guidance for the solution of this problem is considered in paragraph 4-3. Other causes of low penetration resistance include soil freeze, soils with low strength, and driving into a landfill. Materials in landfills will usually be poorly compacted.

(1) Driving of Initial Piles. If the first production piles driven in a group have penetration resistances that are too low, then one must first check to be sure that the hammer and driving energy are adequate and similar to those used for driving near indicator piles prior to or at the start of construction. PDA data must be obtained if the equipment is available, and driving stresses, capacity, and pile quality must be checked. PDA equipment should be available during the driving of the first piles and used to assist the installation.

(a) If pile capacity is not adequate at the embedment depth as indicated by low penetration resistance or the PDA, but the pile is not damaged and driving stresses are satisfactory, several additional piles may be driven as specified in the contract documents. The first piles driven in a group often have penetration resistances that are lower than those driven later. Driving tends to compact the soil and to increase the penetration resistance.

(b) Plot the average penetration resistances of the piles that were driven as a function of time to see if the penetration resistances had increased with time and have reached a satisfactory level. The first piles that were driven in a group should be restruck after driving additional piles to see if the penetration resistances and pile capacity have increased to a satisfactory level.

(c) If the penetration resistances and pile capacity have not increased to an adequate level, then other options should be considered. Such options are driving the piles to a deeper embedment depth, driving additional piles to reduce the spacing between the piles and increase the number of piles in the group, or use a vibratory driver to compact the soil. A cost and efficiency comparison should be made between these options, and the most cost effective option should be selected first.

(2) Piles Driven Later. If piles driven later in a group do not have sufficient penetration resistance, then the cause may be from the effects of soil freeze, from weak soils such as loose sands or soft clays, or from subsurface voids.

(a) If the penetration resistance of the pile remains low when driven, the pile should be restruck after a 1-, 2-, or 5-day delay to determine if soil freeze effects are present. The penetration resistance of restruck piles should be plotted as a function of time to determine the rate of increase in penetration resistance. Adequate capacity may develop after a sufficient delay following pile installation. Soils subject to freeze include loose to medium dense sands, silts, and clays.

(b) If the penetration resistance is low, although driving energy is adequate, there is no evidence of pile damage. If restrike does not provide larger blow counts, then the soils may be weaker than anticipated from results of the exploration program. Driving of additional piles or driving to a deeper embedment depth are options that may be considered.

(c) If the penetration resistance suddenly drops and pile damage is not suspected, the pile tip may have penetrated a subsurface void. The penetration resistance should suddenly increase when the bottom of the void is reached. Driving of piles at nearby locations will aid the determination of the lateral extent of this void. A possible complication with subsurface voids is that they may become larger with time and could eventually compromise the integrity of the foundation. Subsurface voids should be filled with a cement-bentonite grout when they are found. Pile installation should continue at another location of the site until the grout has had a chance to set. If the void in question is an underground cavern (as can occur in limestone), grouting may not be practical because of the size of the void.

b. Problems with High Resistance. Encountered resistance that is too high may be caused by inadequate driving equipment. If the driving equipment, driving energy, and piles are found adequate, then soil relaxation may be a cause of the problem. Relaxation may occur in dense, fine, submerged sand, inorganic silt, or a stiff, fissured clay or by driving a point bearing pile into friable shale or a clay stone. High penetration resistances may also be caused by obstructions such as cobbles or boulders, an unexpected dense or stiff soil, large bodies in landfills, interference with adjacent piles, or bedrock.

(1) Driving Equipment and Piles. Driving equipment that does not have an adequate hammer and driving energy to install the piles will cause high penetration resistances with little or no set of the pile.

(a) The size and type of pile should be checked to be sure that the proper pile is being installed to support the structure.

(b) Contract specifications will provide the minimum driving energy permitted for the work. The driving energy should exceed the minimum permitted energy.

(c) If the PDA indicates that driving stresses are low, efficiency of the hammer is adequate, and pile quality is adequate, energy of the hammer should be increased and driving continued. If the efficiency of the hammer is low, then driving equipment requires maintenance.

(d) If the PDA indicates that driving stresses are high and near the allowable limits and hammer efficiency and energy is adequate, then soil relaxation or obstructions may exist. If soil relaxation or obstructions such as boulders or large bodies are not found, then the soil through which the pile is being driven may be of high strength and assisted installation described in paragraph 3-4 may be required to reach the design embedment depth. Soil data recorded during exploration should be checked to determine if the designers had anticipated high-strength soil at depths above the design embedment depth. Adequate bearing capacity may be obtainable at a lower embedment depth reducing the required length of the pile and save on installation costs.

(2) Relaxation. Penetration resistances that continue to increase as the pile is driven may be caused by soil that increases in strength with increasing depth. Driving may also reduce the pore water pressures and cause the soil strength to increase for a time.

(a) Small displacement piles such as H-piles or open end pipe piles are recommended if relaxation effects are significant. Open-end pipe piles can be cleaned periodically during driving to minimize soil displacement. The pipe pile, after it had been cleaned, can also be filled with an internal core of reinforcement steel and concrete to achieve adequate pile capacity. Consideration may be given to withdrawing the pipe pile as the concrete is being placed if the pipe is not needed to support the concrete or to provide adequate pile capacity.

(b) Driving of the pile should continue until driving stresses reach the allowable limit or until the pile is driven to the design embedment depth. The pile should be restruck after 1 or 2 days, even if the pile had been driven to the embedment depth, to determine if the soil will relax and the soil strength will be reduced following equalization of pore pressures. If the penetration resistance had decreased following the delay, driving can continue until the pile is driven to the design embedment depth or until the driving stresses again exceed the capacity of the pile or the driving system.

(c) Soil strength gain as a result of relaxation can exceed the capacity of the driving system to install the pile. Delays of 1 or more days may be required to drive the pile to the design embedment depth if the capacity of the driving system and/or pile are not increased. The driving energy should be increased until driving stresses reach the allowable limit to optimize driving efficiency. The capacity of the pile may also be increased to avoid excessive overstresses by increasing wall thickness of H-piles or steel open-end piles.

(d) Assisted installation by specialized operations described in paragraph 3-4 is an option that can be used to install piles where relaxation effects are significant.

(e) Several production piles should be restruck after a long term delay such as 1, 2, 5, and 10 days to be certain that long term equalization of pore pressures will not reduce the penetration resistance and pile capacity to excessively low levels. The decrease in penetration resistance recorded during the restrikes should be plotted with time to determine the rate that relaxation occurs. If the decrease in penetration resistance is negligible after 5 or 10 days, then no later restrikes should be necessary.

(3) Obstructions. Obstructions such as cobbles, boulders, and large bodies in landfills will cause significant increases in the penetration resistance leading to refusal of the pile to be driven further and/or the pile can be deflected by the obstruction. The pile will be damaged if driving stresses exceed the allowable limits.

(a) Obstructions near the ground surface are evident by drift of the pile or by abrupt increases in the penetration resistance. Deep obstructions are indicated by an abrupt increase in the penetration resistance or by a significant difference between tip elevations of adjacent piles when the pile had been driven to refusal.

(b) Deep obstructions can deflect the pile without any apparent effect to the exposed portion of the pile above the ground surface. If the deflection breaks the pile, then the penetration resistance may be decreased abruptly. If the deflection caused by the obstruction bends the pile, then the pile capacity may not be adequate. Steel piles can bend through large angles approaching 180 degrees so that the tip is driven toward the ground surface and may even break the surface.

(c) Obstructions may be removed by assisted installation or may be pierced with a spud. A spud is a mandrel, heavy steel pipe or H-pile section driven to provide a pilot hole. The spud is withdrawn and the pile inserted into the hole and driven to the embedment depth.

(d) A production pile may also be pulled when difficult driving is encountered and redriven. However, skin friction may be reduced causing these piles to be unacceptable friction piles.

c. Problems with Ground Movement. Displacement piles such as timber, precast concrete, and closed-end pipe piles displace the ground as they are driven to the embedment depth. Driving these piles in dense sands or saturated cohesive soils will probably cause heave of the ground surface around the driven pile.

(1) Heaved Piles. Piles that heave should be redriven to their original embedment elevation, but

redriving should not begin until all heave had occurred. The penetration resistance required to redrive the piles to the embedment elevation should be recorded and, any significant change in the penetration resistance should be noted.

(2) Adjacent Structures. Increases in surface elevation exceeding 0.5 inch may cause damage to adjacent structures. Therefore, the effect of ground heave from pile installation should be observed on adjacent structures.

(a) The increase in the surface elevation from ground heave should be measured and recorded.

(b) Ground heave near adjacent structures should be controlled if this heave exceeds 0.5 inch. Methods of controlling ground heave include pre-excavation, increasing pile spacing, or by installation of small displacement piles.

d. Problems with the Environment. All environmental requirements will be fully addressed prior to construction and necessary approvals fully documented.

(1) Vibrations and Noise. Pile driving operations produce considerable noise that may adversely influence the well-being of inhabitants of the area.

(a) Vibrations can damage nearby structures. Structures adjacent to the construction will be monitored to assess their integrity prior to and during construction. Assessment of the integrity of adjacent structures is required prior to construction to determine the initial status of the structures.

(b) Noise can interfere with the quality of life and cause hearing loss to people. High noise levels that are part of an impact hammer pile driving operation can and frequently do prevent installation of driven piles where people can be adversely affected. People within range of damaging noise levels will be protected with safety measures. Vibratory drivers produce much lower noise levels than impact hammers and should be used where noise can be harmful.

(2) Hazardous Materials and Gases. Some construction sites may be located in areas that had been used for landfills, storage depots, or contain natural gases.

(a) The environmental requirements for the site must have been fully addressed prior to construction. Therefore, this is a complication that is not expected, and this situation should not occur. This is an important reason for thorough exploration prior to construction.

(b) If hazardous materials or gases are suspected during pile installation, then the construction activity will be delayed until an environmental assessment can be completed to check this complication. Hazardous materials or gases can become evident when piles are extracted or when the soil collected in hollow open-end piles during driving is excavated.

(3) Groundwater. The exploration program is expected to determine the elevation of the phreatic surface and any evidence of artesian and perched water.

4-5. PERMAFROST AREAS. Frozen soil often has high strength similar to rock. Installation of piles with impact hammers or even vibratory drivers may be impractical and alternative installation methods are required.

a. Site Preparation. The site should be prepared to promote equipment mobility and access at a later time in case other work is necessary.

(1) Disturbance of the ground surface during the construction season frequently increases the depth of thaw. This causes the surface to loose trafficability. The ground surface should be covered with a blanket of gravel or broken stone and work performed from on top of this blanket.

(2) Access to all of the equipment should be limited to the immediate vicinity of the area where the installation is to occur. This area should be prepared so that access of equipment to the area is permanent in case work is required later. For example, maintenance work will probably be required at some later date.

b. Method of Installation. Piles in permafrost areas are not driven to resistance, but rather to some specified tip elevation. Refreeze of the soil around the pile must occur as quickly as practical to develop the required pile capacity. This capacity comes from adherence of the soil to the pile and must support the downward loads and have sufficient resistance to frost heave. Methods of installing piles that can accomplish adequate pile capacity is by drilling or by steam jetting.

(1) Drilling. This method consists of the dropping of pile sections into a boring hole that is made dry with an auger or with a rotary drill and slurry.

(a) Truck mounted augers are usually applicable in silts, clays, and some sands. A rotary drill or local prethawing may be required in coarse sands and in soils containing cobbles.

(b) The excavation after placing the pile sections is backfilled with a soil-water slurry that bonds to the pile on freezing. The slurry should be placed in the hole at near freezing temperature to minimize refreezing time.

(2) Steam Jetting. This method consists of thawing a vertical shaft of soil by a steam jet, pressing or driving the pile into the shaft of thawed soil, and allowing the thawed soil to refreeze.

(a) A 0.75 to 1.25 inch pipe, open or slightly crimped at the point to give better jetting action is used with steam pressures from 100 to 200 psi. A chisel bit may facilitate penetration in gravel.

(b) Water should be added to the jetted shaft in dry soil to promote thawing.

(c) If the thawed shaft of material is of small diameter, then the steam jets should be worked alongside the pile as the pile is advanced down the thawed shaft.

(d) The thawed volume of soil should be minimized to reduce refreezing time.

(3) Seating the Pile. The tip of the pile section should be seated firmly on the bottom of the excavation or thawed shaft of soil to obtain partial capacity and to be able to support the weight of the construction while the adfreeze is developing between the soil and the pile.