CHAPTER 3
SITE INVESTIGATIONS

3-1. General.

a. The site data needed for design of foundations in cold regions include the same information as would be required in temperate regions, but with additional requirements imposed by the special climatic conditions. Also the remoteness of the site often imposes additional requirements[155]. Subject to design policies, general criteria, cost limitations and the constantly changing state-of-the-art, site information needed for design of foundations in cold regions may be summarized as follows:

Climate (general and local).
Physiography and geology, including topography and surface cover.
Subsurface conditions.
Thermal regime.
Hydrology and drainage.
Materials of construction.
Transportation facilities and access.
Construction cost factors.

b. Availability of labor, construction equipment and supplies. Must of the information needed for foundation design must be obtained as a part of the over-all facility design. However, some elements of needed information pertain specifically to foundations.

c. By giving adequate attention to subsurface conditions during the site selection stage, foundation design problems and facility costs can often be greatly reduced. When facilities can be sited on deposits of deep, free-draining, non-frost-susceptible granular materials, design, construction, maintenance, and operational problems are all minimized.

d. When a facility such as a power transmission line or long pipeline covers an extended area, not only may a variety of foundation conditions be encountered but also a considerable range of ground temperatures and permafrost conditions. In such cases it 'will be uneconomical to develop an individual design specifically for each structure or portion of the facility. Instead, the terrain may be divided into areas of like foundation conditions, and standard designs prepared which will be suitable over each of these areas. Also, a number of standard designs may be prepared to cover the range of conditions, the particular design for each facility element to be field-selected in accordance with the conditions actually encountered.

3-2. Remote sensing and geophysical investigation.

a. Aerial investigation techniques are especially valuable during the selection of the site location itself. At times communications or other requirements may closely dictate the choice of the facility site. Often, however, the opposite is true and site selection may involve hundreds or even thousands of square miles of potential terrain. In such cases, remote sensing and geophysical techniques may provide the only economical approach. State-of-the-art reviews are continued in publications by Ferrians and Hobson[142] and Linell and Johnston[165]. Use of conventional aerial photographic techniques for terrain and site investigation in arctic and subarctic areas began in the late 1940's and the results were reported by Frost[62]. The U.S. Army Corps of Engineers has included summaries of these techniques in two Engineering Manuals. Aerial photography and photo interpretation are invaluable in obtaining much of the needed site information and should be employed routinely as part of design studies. Information obtained by aerial photography should be tied in with coordinated ground investigations. The ground studies will provide reference data and accuracy checks of the aerially obtained data and should extend this information in the detail necessary for actual design. The accelerating development of northern North America in recent years has greatly spurred practical use of these techniques, particularly in connection with investigations for several pipelines[172].

b. Color and infrared photography, and radar and other special forms of sensing techniques may also be employed. Rinker and Frost have recently discussed the application of various type of remote sensing to environmental studies in the Arctic[182]. Haugen et al.[151] and Ferrians[141] are currently investigating potentials for satellite acquisition of data under the Earth Resources Technology Satellite (ERTS) program, obtaining information on such surface details as vegetation, snow and ice cover, ground temperatures, geomorphic and other evidences of permafrost, stream levels, sedimentation patterns, and forest fires. Electromagnetic sensing systems, both airborne and surface operated, have been shown capable of distinguishing with depth materials such as soils, ice and rock having different electrical properties,[142,144,147], to depths of 15 meters or more in frozen ground. Although not yet routinely used, such equipment is in a state of rapid and continuing development. Garg[147] and Hunter[152] have reported that both resistivity and refraction types of conventional geophysical systems have utility in permafrost areas, and Roethlisberger[84] has summarized the state-of-the-art of seismic exploration in cold regions. Development of acoustic reflection type sounding equipment for use in permafrost areas is in a very early state of development. Greene[149.163] and LeSchack[162,163] have concluded that infrared sensing techniques can provide useful information on permafrost conditions. Ferrians and Hobson[142] have reviewed the currently available information on applicability of bore hole logging methods in permafrost areas. Williams and VanEverdingen[209] have also concluded that borehole geophysical logging methods can yield valid geophysical logs in frozen unconsolidated deposits and that interpretation is possible in terms of bulk density, moisture content and other characteristics.

3-3. Detailed direct site exploration.
Guidance for foundation investigation is given in TM 5-852-2/AFM 88-19, Chapter 2 [11] and TM 5-818-1/AFM 88-3, Chapter 7 [5] and is also discussed in Terzaghi and Peck[198]. Detailed direct investigations of site conditions are required at structure sites. Positive knowledge of subsurface conditions is as important in foundation design as is knowledge of properties of construction materials in design of above-surface structures.

a. Extent of exploration. The number and extent of direct site explorations should be sufficient to determine in detail the occurrence and extent of permafrost, ground ice, including ice wedges, moisture contents and ground water, temperature conditions in the ground, and the characteristics and properties of frozen materials, soil and rock. It is desirable that the personnel who make the actual site investigations proceed in very close communication with the design engineers so that a continuous process of feedback and adjustment of the investigation program can be maintained; as a minimum, the field personnel must be aware of the features which are important in foundation design in general and of criteria applicable for the particular facility.

(1) A thorough soil investigation should be conducted for all new construction. Sites with granual soils free of ice masses are highly desirable for siting of structures, and although sands or gravels of soil groups GW, GP, SW, and SP are generally free of segregated ice, this is not necessarily true in all cases. Granular soils often occur as a cap over finer grained soils containing ground ice and superficial investigations based only upon the nature of the surface materials may lead to very serious problems, possibly many years after completion of construction. Buried ice wedges, old stream channels, and peat deposits containing excess ice may be present. As figure 3-1 suggests, a single shallow exploration, or a few widely scattered ones may fail to reveal the true subsurface conditions. Experience also shows that bedrock often contains substantial masses of ice which would produce substantial settlement on thaw; bed rock thus cannot automatically be assumed to provide a sound foundation. Bedrock should be explored by core boring methods to obtain undisturbed frozen cores whenever this possibility would be a factor in the foundation design.

(2) Explorations at the structure site should extend to a depth at least equal to the least width of the foundation, unless icefree bedrock is encountered at shallower depth. In addition, the explorations should encompass any foundation materials subject to possible thaw during the anticipated life of the structure, as illustrated in figure 3-1. For structures with pile foundations, the explorations should establish the nature of materials in which the piles will be supported.

b. Techniques of subsurface exploration. Frozen soil may have compressive strength as great as that of lean concrete (para 2-5). Frozen glacial till at very low temperatures has been described as behaving exactly like granite in excavation and tunnelling work. These properties make subsurface exploration in frozen materials considerable more difficult than in unfrozen soils and sometimes have led to accomplishment of less subsurface exploration than needed, with disastrous results. Persons responsible for subsurface exploration, therefore, should be prepared to bring extra money, effort, talent, and equipment to bear on the problem.

(1) Deep core drilling using refrigerated drilling fluid to prevent melting of ice in the cores gives the best results under the widest range of materials up to and including frozen soils containing particles up to boulder size and frozen bedrock.[153,161] Cores obtained by this procedure are nearly completely undisturbed and can be subjected to the widest range of laboratory tests. They permit ice formations to be inspected and measured accurately after removal of the drilling-fluid-saturated out surface. Cores should be photographed for record purposes when appropriate, and when low temperature storage cannot be provided. In fine grained soils above 25° F, drive sampling is feasible[55] and is often considerably simpler, cheaper, and more rapid. Samples obtained by this procedure are somewhat disturbed but they still permit accurate detection of ground ice and accurate moisture content determinations on specimens. Examination and sampling of natural and man-made exposures in the general site area may be helpful but care is necessary to avoid being misled by sloughing of the face or by rapid melting and disappearance of ice when air temperatures are above freezing.

(2) Test pits are also widely useful, especially in shallow granular deposits intended for borrow. For frozen soils, which do not contain very many cobbles and boulders, truck mounted power augers using tungsten carbide cutting teeth provide excellent service where classification, gradation and rough ice content information will be sufficient; this procedure is very useful for expansion of subsurface information where critical details have already been established by more widely spaced undisturbed core drilling techniques. In both seasonal frost and permafrost areas a saturated

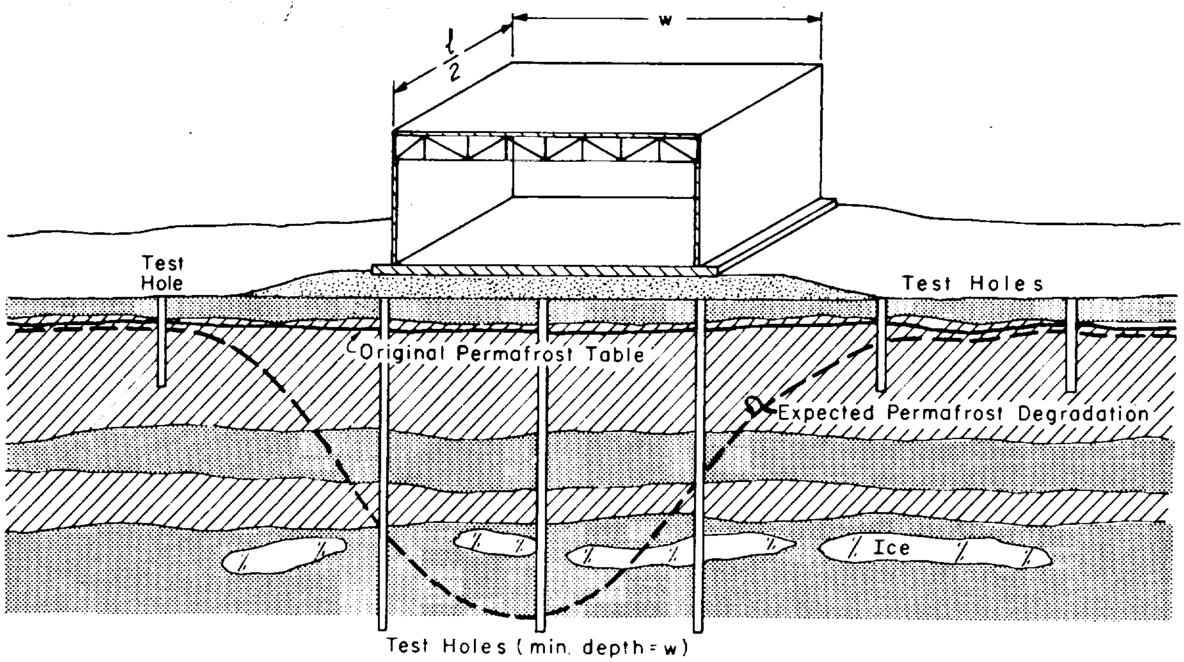

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Figure 3-1. Required extent of explorations for large structure.

condition is common in the upper layers of soil during the thaw season so long as the underlying layer is frozen impervious soil. Normally, borings must be cased through this saturated thawed layer. It is frequently found that explorations are most easily carried out during the colder part of the year, when water areas and the annual frost zone are solidly frozen, rather than during the summer.

c. Special investigations. Special investigations may be necessary for unusual projects; for example, the installation of a nuclear power plant may require installation of temperature sensing equipment on a mush more elaborate scale than for an ordinary structure. Again, for structures in which the dynamic response of the foundation is important, measurements may be required of dynamic modulus and wave propagation velocities in the field and in the laboratory. In other cases creep deformation of electrical properties of the foundation (such as for grounding of antennas) may be critical. Installation of test piles may be required during the site investigation or early construction phases in order to determine optimum methods of installation and the actual allowable loadings and performance of piles. Sometimes other field experiments may be required in order to determine if new or untried construction methods are feasible under the particular soil and temperature conditions.

3-4. Site technical data. Careful collection of data as outlined in the following paragraphs of this Chapter as applicable will provide a reliable picture of the natural subsurface conditions existing at a specific site and will provide a solid base of information for consideration of design options and performance of most design analyses. Additional special technical data development may be required, depending on the specific type of foundation design to be explored. This may involve either laboratory or field tests, or both. Field tests must normally be performed at the naturally occurring field ground temperatures; if the tests cannot be performed at the critical design temperatures because of time or other requirements, the results must be adjusted or extrapolated to these temperature conditions. Laboratory tests may be performed at coldroom or test chamber temperatures which are representative concontrolling field conditions and also permit economical investigation of the effects of full ranges of conditions. If the general site conditions have become clearly established in previous design studies at the particular location, foundation studies for subsequent facilities construction may often be less extensive and may in fact sometimes consist mainly of verification explorations. General information requirements for site selection and development have been outlined in preceding paragraphs and are given in detail in TM 5-852-2/AFM 88-19, Chapter 2 [11]. The following discussion is limited to specialized aspects of cold regions foundation design for a specific facility.

a. Climatic data. Some climatic data such as temperature information will provide direct input to the technical foundation design. Other data will provide indirect input, such as weather conditions which will be experienced during the construction period, including the lengths of the outdoor working seasons and of the specific periods over which protection against adverse temperature conditions will be required. Freeze and thaw indexes are essential for computing depths of freeze and thaw and for estimating degradation or aggradation. Precipitation is an indicator of both outdoor working conditions and of surface and subsurface drainage conditions. Snowfall amounts, the frequency and intensity of snow drifting, snow depths, and the frequency and intensity of icing conditions are all important input elements affecting directly or indirectly the foundation design. The deposit of ice and snow may frequently impose severe loads on structures and foundations. It is important to tabulate liquid and solid types of precipitation separately. When snow drifting patterns may be important to the operation and maintenance of the facility, it is desirable to obtain aerial photographs in the spring after initial thaw has started to delineate sharply the natural patterns of seasonal accumulation. Information on wind directions and velocities and the frequency of storms is essential in design of structures and it is one of the determinants of foundation design loading values. In mountain areas, structures may require design for velocities as high as 200 to 250 mpg, imposing severe foundation stability requirements. Often foundation uplift forces produced by wind on specialized structures such as antennas offer the most critical foundation design problems in permafrost areas. If added footing weight and size or added depth of footing burial is required to resist uplift, this may result in substantial revisions of the ultimate design. Combinations of severe climatic conditions must also be investigated. For example, severe icing conditions combined with high wind may be critical for a radio transmission tower. When there are no weather records from' a station near the proposed site, it will be necessary to estimate conditions at the site from weather records at the nearest available locations, taking into account such factors as latitude, elevation, exposure, and nearness to water bodies. Experience shows that this estimation is difficult to accomplish with accuracy. Therefore, whenever the time and nature of the job permit, arrangements should be made for collection of at least elementary weather data at the site itself at the earliest possible time; even records for part of a year may give invaluable checks on the accuracy of estimates. Sometimes design, maintenance and/or operational difficulties may be substantially simplified by small, local adjustments of site location based on detailed knowledge of local conditions.

(1) Specific weather information useful in foundation design includes mean, minimum, and maximum daily air temperatures; precipitation (liquid and solid); snow and ice depth on the ground; wind velocity and direction; and frequency of storms or severe combinations of conditions. Air temperatures are the most important data; they are obtainable with a simple recorded needing a minimum of attention.

(2) Even observations for a limited period such as a month, when compared with simultaneous observations at the nearest regular weather stations, will give valuable clues concerning the air temperature regime of the structure site.

(3) Equipment, installation and observational procedures should be in accordance with the guidance of the National Oceanic and Atmospheric Administration Federal Meteorological Handbook No. 2, Substation Observations[178]. Greater technical detail is available in Handbook No. 1, Surface Observations[177].

b. Subsurface thermal regime. Ground temperatures with depth have been recorded for numerous specific locations in North America and Greenland, including a number of stations in Alaska[10,25,29,37,99,101,102]. Data from such observations and air temperature records, together with detailed data on topography, elevation, snowfall and other site data, permit approximate preliminary estimates of ground temperatures at new sites. However, it is very easy for such estimates to be considerable in error unless all pertinent factors are accurately perceived and evaluated. For example, permafrost is found in the valley bottoms in the Fairbanks, Alaska, area but is absent in valley bottoms in the Knob Lake, Quebec, area in spite of a lower mean annual temperature. One key reason for this is the much heavier snowfall in the latter area. Again, at Kotzebue, Alaska, mean ground temperature in the gravel spit on which the village is located is about 29.7 °F but it is about 24.5 °F in the silt and clay bluffs which are at only slightly higher elevation but are more removed from direct contact with the effects of the ocean.

(1) At new sites, ground temperature and freeze and thaw penetration information should be obtained as early as possible in the site investigations, in sufficient detail to demonstrate or verify the subsurface thermal regime. Copper-constantan thermocouples installed in foundation exploration holes or in holes drilled for this specific purpose provide the simplest means of measuring subsurface temperatures. Readings with an absolute accuracy of about ± 0.4°C (3/4°F) may be obtained manually using a portable potentiometer. When greater precision is needed than is obtainable with thermocouples, thermistors of a select type, glass-bead encased and properly calibrated, should be employed. Careful techniques can readily produce data from ther-

mistors accurate to ± 0.01 °C (0.02 °F), although under field conditions with less than fully experienced observers, a lower order of accuracy may be obtained. A more detailed discussion of temperature sensors is presented in chapter 7 (para 7-4). To obtain a good measure of the mean annual ground temperature, at least one temperature installation should extend to a depth of about 30 feet. Readings during the period of thermal stabilization following installation should be discounted. Readings during the summer and fall when readings in the upper part of the foundation are at their warmest are most important. One or more of these assemblies should be installed in areas which will not be disturbed by the construction, in order to serve as a control against which ground temperatures in the construction area during and after construction may be compared.

(2) The maximum seasonal depth of thaw penetration can be readily measured at the end of summer or in early fall by probing, test pitting or other means, correlated with soil temperature readings.

(3) Thermocouple and thermistor assemblies are usually prefabricated in protective plastic tubing before delivery to the site. Recommended principles and techniques of subsurface temperature measurement are presented in a paper by Sohlberg;g2 his report includes an extensive bibliography.

c. Physiography and geology. Even if only a single structure is involved, physiographic and geologic information on the general area should be established. Information on the surrounding terrain will often be invaluable in interpretation of the detailed exploration results at the site itself. Bedrock exposures, glacial landforms, alluvial deposits and similar features should be known. Surface cover conditions of the site should also be recorded and are essential for estimating the extent of change in thermal regime which will be produced by the construction. Topographic data are an essential requirement.

d. Identification and classification of foundation materials. The most important single step in foundation investigations is the accurate description and classification of the exploration materials in accordance with the Unified Soil Classification System MIL-STD 619B including the frozen soil classification system.' The frozen soil portion of this system has been devised on the basis of experience of United States and Canadian organizations[167].

(1) The frozen soil classification system provides information on the factors of appearance and physical properties which are essential guides to the nature and behavior of the material in the frozen state and to the changes which may occur upon thawing. It is independent of geologic history or mode of origin on the materials and can be used with any types of samples which show the natural structure of the materials, such as specimens recovered from drill holes or test pits, or frozen in the laboratory. Unfrozen soils and the soil phase of the frozen materials should first be identified; the material characteristics resulting from the frozen state are then added to the soil description as appropriate. Important ice strata found in the foundation are then described separately.

(2) Frozen soils are divided into two major groups: soils in which segregated ice is not visible to the naked eye, and soils in which segregated ice is visible. The visual division is not necessarily determinative for thaw settlement potential. The boundaries between frozen and unfrozen strata should be carefully recorded, particularly in marginal permafrost areas. Surface cover materials should be included in the exploration records and should be described especially carefully. Tests in the field and/or laboratory such as for soil gradation and Atterberg Limits may be employed as needed to supplement the field identification.

(3) The result will be an exploration log of the type illustrated in figure 3-2, where an obvious thaw settlement potential exists, as revealed by the ice layer from 7.7 to 9.1 feet. This information may by itself decisively limit the design options and determine the needs for further foundation data.

e. Density and moisture content. The dry unit weight and natural moisture contents of both frozen and unfrozen core samples or frozen lumps should be determined. The bulk densities of representative frozen core samples or frozen lumps should be first obtained. Then the sample should be melted and the dry weight of solids and the moisture content as a percent of dry unit weight obtained. This will give a plot of dry unit weight and moisture content vs. depth as shown in figure 3-3. From knowledge of the common moisture content ranges for the foundation materials encountered and from the number and thicknesses of ice layers encountered, the existence of a potential settlement problem in thawing may be immediately apparent if amounts of ice are appreciable. However, quantitative analysis of the amount of settlement which will occur can readily be made through the procedures outlined in *f* below.

(1) The maximum heave that can occur as a result of in-place freezing of the water present in the voids of a non-frost-susceptible soil (without ice segregation) may be computed by the following formula:

$$\Delta H = 0.144 w \lambda_d H \times 10^{-4} \quad \text{(Equation 1)}$$

where

ΔH = frost heave, ft

w = water content, percent of dry weight of soil

Δ_d = dry unit weight of soil, lb/ft^3

H = thickness of deposit, ft.

(2) The expansion on freezing of non-frost-susceptible soil is negligible under nominal confinement

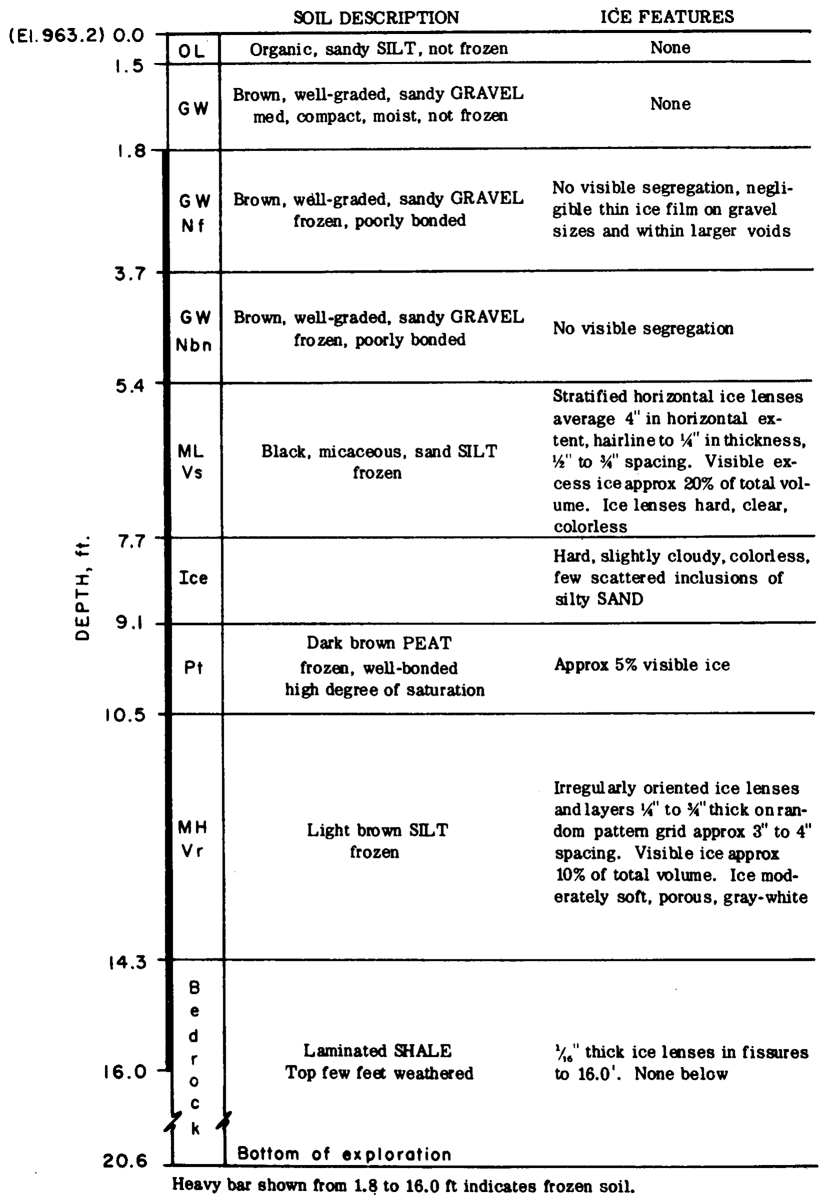

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Figure 3-2. Typical exploration log.

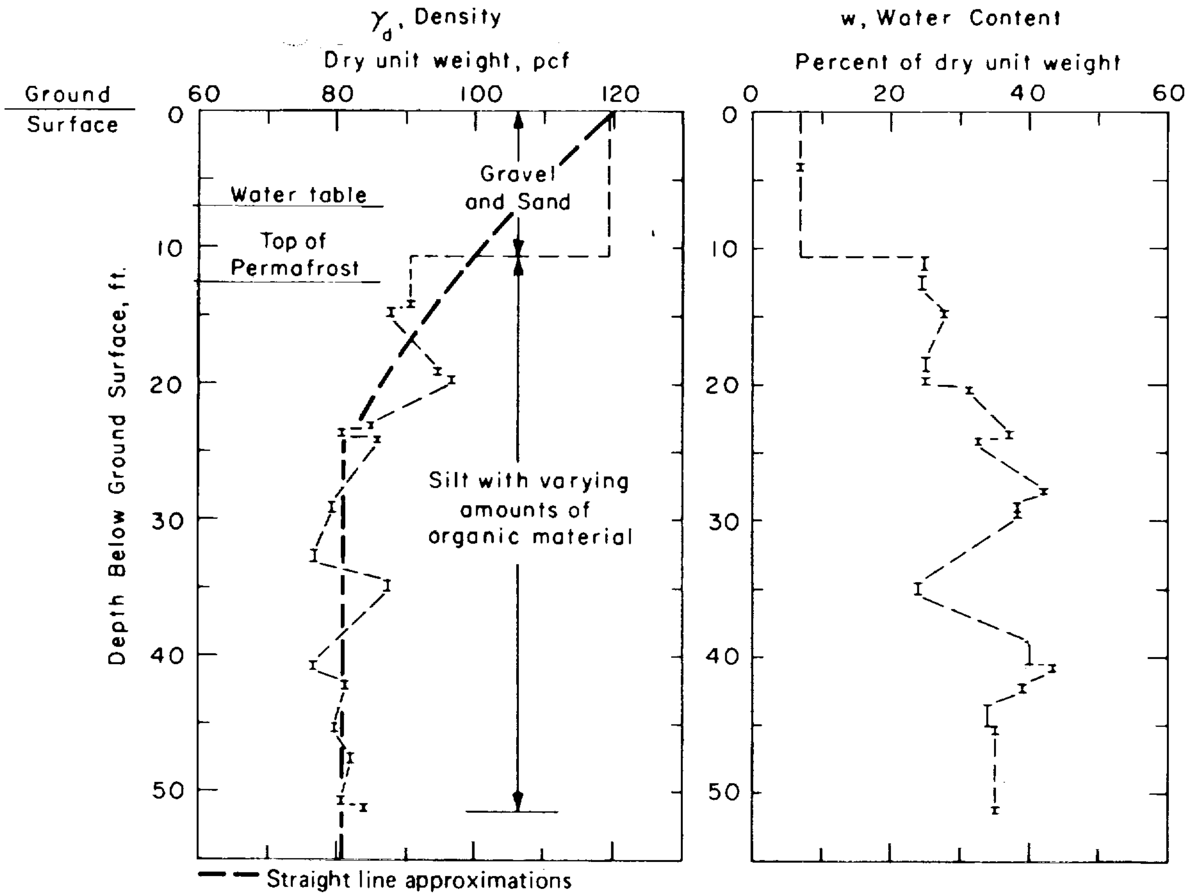

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Figure 3-3. Dry density and water content vs. depth for a soil exploration in permafrost.

if it is sufficiently well-trained so that the excess volume of water corresponding to the expansion of water upon freezing can escape. The top few inches of soil, under less than 1 psi of confining pressure, may "fluff" during freezing; this is usually of negligible practical importance except to trafficability in the thawing season. However, because natural soil may not be completely non-frost-susceptible and because drainage below the plane of freezing may not always be perfect, freezing of upper layers of soil may have made them less compact than underlying materials. This effect may extend as deep as 30 feet.

f. Thaw-consolidation and settlement. When quantitative data are needed on the amount of settlement which will occur on thaw under the foundation stresses which will exist after construction, rapid estimates may be made by cumulatively measuring amounts of ice visible in core samples or in test pit or excavation exposures. If amounts of ice are substantial these results may be determinative. For less clear-cut situations, such as where ice is relatively uniformly distributed through the soil rather than occurring as individual ice layers, where clear ice is apparent but there still may be direct particle to particle contact in the soil structure, or where swelling rather than reduction in volume may occur, thaw consolidation tests would be performed on frozen, undisturbed samples. Crory[135] and others have discussed test procedures and analyses. Two methods of performing such thaw consolidation tests are available. In one, frozen core samples are trimmed under coldroom conditions to fit a standard soil consolidometer apparatus.[135] An initial compressive stress, nominally 1 psi, is applied to the frozen specimen; it is then allowed to thaw and consolidate (or swell) under this stress to determine the consolidation which is attributable primarily to the ice content of the specimen. Consolidation is allowed to continue until at least primary consolidation is complete. Secondary consolidation may rarely have to be taken into account. Successive increments of load are then applied in accordance with conventional test procedures to develop plots of pressure versus void ratio as illustrated in figure 3-4 or pressure versus settlement strain as illustrated by figure 3-5 to encompass the stress level which may be expected in the foundation. The amount of settlement which may be expected at the level in the foundation represented by the specimen may then be computed from the volume change information. Note in figure 3-5b that the initial compressions of samples which are thawed after application of the initial load were much more than for the samples thawed *prior* to application of the initial load. Where time-rate of consolidation information is needed it can be computed from the individual incremental compression versus time records.

(1) As an expedient method to obtain a measure of the volume reduction which may occur on thawing of materials which cannot conveniently be trimmed to fit into a standard consolidometer, a lump of the frozen material may be placed into a bag of thin rubber together with a length of tubing attached to a porous stone or other drainage medium. After evacuation of the rubber bag sufficient to bring it into intimate and complete contact with the frozen soil, the initial volume of the bag and sample should be determined. The specimen should then be thawed under about 1 psi vaccuum pressure differential with drainage of the excess water permitted to occur through the tubing. The volume change of bag plus sample should be measured when thaw is complete and again after completion of each successive consolidation pressure increment which can then be effected under external pressure. The resulting volume change information may be taken as indicative of the amount of settlement which will occur on thaw. The lump method is not suitable for depth-time rates of consolidation as the lengths of drainage paths are indeterminate. The results may also involve some error from the fact that the consolidation effected is not unidirectional nor related to foundation strata in the same manner as in the actual foundation. However, since a large portion of the consolidation may commonly be that resulting from the thaw of ice, as illustrated in figure 3-5, the test may be a quite useful indicator.

(2) From plots of soil density with depth and with addition of structure load stresses, the relationship of intergranular pressure with depth for the design condition should be established as illustrated in figure 3-6. Using this information and the pressure versus void ratio or pressure versus settlement strain consolidation data, and cumulatively summing the amounts of settlement associated with increasing increments of thaw depth, curves of estimated settlement vs. depth of thaw may be estimated, as illustrated in figure 3-7 and table 3-1 for individual locations. If the foundation materials

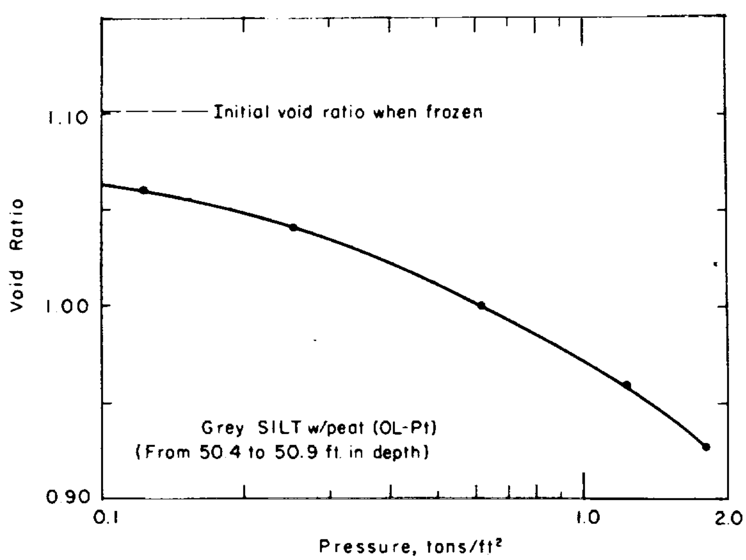

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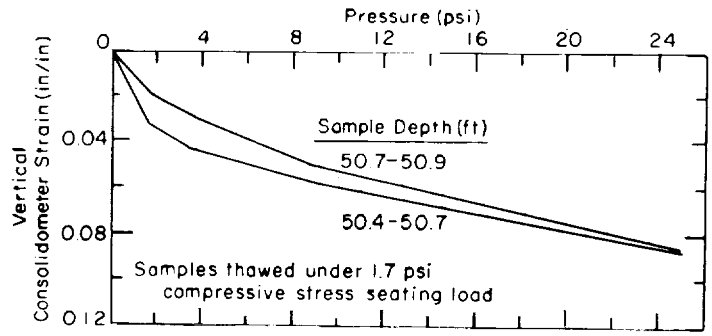
Figure 3-4. Thaw-consolidation test on undisturbed sample.



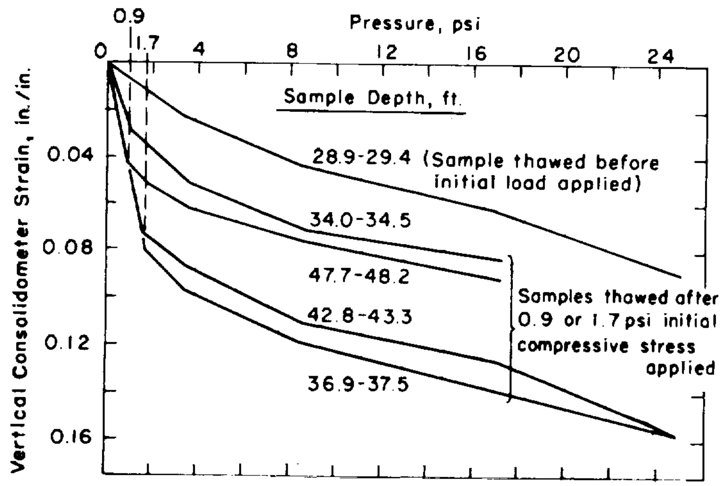


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Figure 3-5. Consolidation test results for undisturbed samples from two drill holes at same site. Tests performed using fixed ring consolidometer. Specimen diameter 2.5 in., height 0.8 in..

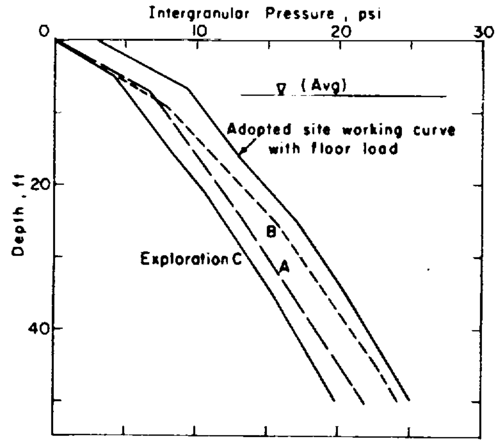

Figure 3-6. Intergranular pressure vs. depth for three explorations at same site. Site work curve based on average of A, B and C, to which was added a 2-psi floor load. Curve A was computed from density data in soils of figure 3-3, using straight line approximations.

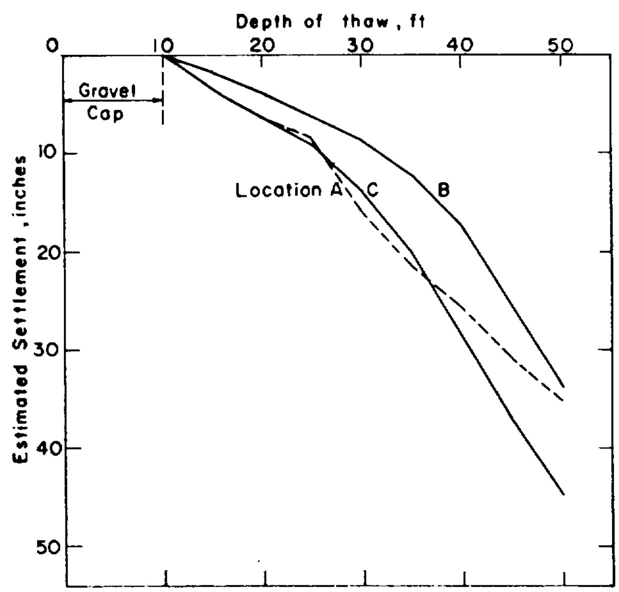

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Figure 3-7. Estimated settlement vs. depth of thaw for different explorations at the same time.

Table 3-1. Example of Settlement Estimate - Location A, figure 3-7.

Depth (ft)	Average pressure (psi)	Strain (in./in.)	Settlement of layer (in.)	Cumulative settlement (in.)
10-15	11.6	0.0o64	3.84	3.84
15-20	13.6	0.036	2.16	6.00
20-25	15.8	0.0425	2.55	8.55
25-30	17.8	0.124	7.44	15.99
30-35	19.6	0.088	5.28	21.27
35-40	21.2	0.071	4.26	25.53
40-45	22.8	0.089	5.34	30.87
45-50	24.3	0.070	4.20	35.07

Notes: 1. Values for average pressure determined from "Adopted Site Working Curve" in Figure 3-6.

2. Values of strain for first five layers taken from plots of pressure vs strain in Figure 3-5a for Exploration A. Values for three lower layers determined from similar plots not shown.

may be expected to consolidate nearly as rapidly as thaw progresses, the rate of settlement will correspond closely in time with the rate of thaw. Because the thaw front under a heated structure advances more rapidly at the center than under the edges, as illustrated in figure 4-9, the actual distribution of settlement displacement across the foundation normally will develop in a dish shape.

g. Thermal properties. The basic thermal properties of soils and other construction materials pertinent to foundation design are specific heat, thermal conductivity and latent heat of fusion. Satisfactory values of thermal conductivity and specific heat of these materials for design computations are available in tables and charts of TM 5-852-6,[14] the values for soils and rock being based primarily on investigations by Kersten." Because special equipment is required, special measurement of perties for design purposes is not recommended for normal design situations.

(1) If performance of thermal conductivity tests is required, however, it is recommended that the guarded hot plate method be used, ASTM C 177,[119] with equipment modified to maintain specimen temperatures below freezing. CRREL has test apparatus of this type and has performed research on thermal properties of construction materials at below freezing temperatures.[71] Thermal conductivity probes have been extensively investigated[108,171] but procedures which will produce reliable results under all conditions have thus far not been developed.

(2) The thermal conductivity of soil is dependent upon a number of factors such as density; moisture content; particle shape; temperature; solid frozen, unfrozen, or partially frozen. The latent heat of fusion 6f soil is dependent upon the amount of water in the voids which actually freezes. The specific heat capacities of soils may be adequately computed by summing the specific heat capacities of each constituent, multiplied by its respective mass fraction, taking into account moisture phase proportions. Anderson and Tice[123] have made detailed investigations of the unfrozen water contents in frozen soils and Anderson and Morgenstern[121] have recently summarized other related fundamental thermal research since 1963.

h. Ground water records. Knowledge of surface and subsurface drainage and water table conditions of the general area is needed for accurate design. Under bodies of water, the permafrost table may be depressed or permafrost may be absent, particularly in marginal permafrost areas, and subsurface movement of moisture through these unfrozen zones may be an important factor influencing the thermal stability of the foundation. It may also be possible to exploit such zones as water supply sources.[191,209] When residual thaw zones carrying subsurface drainage develop, the thaw zones tend to deepen and channelize and when these develop near a foundation, they may threaten its stability. Even where moisture-bearing residual or permanent perched thaw zones do not exist, substantial quantities of water and heat may be transported by subsurface flow in the annual frost zone in the summer. Thus sufficient information is needed so that both surface and subsurface drainage conditions within the vicinity of the structure and foundation after construction can be anticipated.

(1) Ground water levels encountered in subsurface explorations should be recorded routinely, whether in seasonal frost or permafrost areas. In the saturated silty soils common in permafrost areas, as illustrated in figure 2-4, the ground water table in the annual frost zone may drop rapidly during the fall and early winter and disappear well before annual freezing reaches permafrost level. However, as further illustrated in figure 2-4, frost heave may continue almost up to the time freeze-up is complete because, in frost-susceptible finegrained soils, 95 percent or higher degree of saturation may still prevail at the moment when removal of moisture causes a free water table to disappear. In permafrost areas the absence of a water table in the annual frost zone in the freezing season should not be taken to indicate that high ground water will not exist in summer.

(2) Ground water considerations are further discussed in Chapter 4 (paras 4-12 and 4-18) and Chapter 7 (para 7-6).

i. Frost susceptibility. Criteria for susceptibility of soils to ice segregation based upon the percentage of grains finer than 0.02 mm by weight are outlined in TM 5-818-2[6]. While 3 percent finer than 0.02 mm is the most common dividing line between soils susceptible and not susceptible to ice segregation, frost heave and subsequent thaw weakening, and is used widely in pavement engineering, this is a very rough measure, an engineering rule of thumb, signifying not zero frost susceptibility but a level which is acceptably small for most engineering requirements under average conditions. For a specific soil, the actual limiting criterion for frost susceptibility may be either below or above this value. For borderline materials or where a measurement of frost susceptibility is essential, freezing tests will be carried out under the supervision of the U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. Because of possible serious structural and operational effects of differential frost heave, the site investigations should ascertain the horizontal variability of frost heave potential under the structure. Variation may occur from point to point as a result of differences in soil type, properties or profile, or in moisture availability. Figure 3-8 illustrates a special case of such variability which resulted in serious cracking, in the first winter, of a new rigid pavement at the west end of the East-West taxiway at Elmendorf AFB, Anchorage, Alaska, with 72 inches combined thickness of pavement and non-frost-susceptible base over the natural soil subgrade. Maximum heave was about 0.4 feet. The pattern of cracking shown in figure 3-8, which also continued out through the unpaved shoulders, directly corresponded with a pattern of extreme subgrade soil variation. The soil conditions are illustrated by a profile recorded in a trench dug parallel to the south edge of the taxiway, (fig. 3-9). The Alaska District, Corps of Engineers, concluded that the alternating strata of sands and silts had been contorted by glacial shoving into their near-vertical positions. It will be apparent that design of structure foundations on such soils would require special attention to the subsurface details.

j. Frost heave field observations. It is often necessary or useful to have quantitative information on the amount of frost heave which occurs at a project site. Since heave and settlement are cyclic, the amount of frost heave can be determined by measuring either total heave, which occurs during fall and winter, or total thaw settlement, which occurs in spring and summer. Aitken2' describes one type of apparatus used in measuring frost heave of the ground surface. Where roads exist, the amount of heave may be determinable at fixed structures such as bridge abutments or culverts. Effects of frost heave or frost thrust can often be discerned by the evidence of frost jacking out of the ground or tilting of insufficiently anchored and inadequately constructed facilities. In summer, mud lines may often be discerned on surfaces of piles or structures as the heaved surface recedes with thaw. Thaw consolidation tests can also be performed on cores of frozen materials obtained from the annual frost zone after maximum winter freeze had occurred. Where some frost heaving of the facility under design is to be permitted, as for a transmission tower, but the amount must be limited, the design predictions may be verified by constructing a prototype foundation without superstructure but with equivalent ground cover, loading it, and observing its performance through a freezing season.

k. Creep and solifluction. Slope creep is extremely slow downslope movement of surficial soil or rock debris, usually imperceptible except by long-term obser-

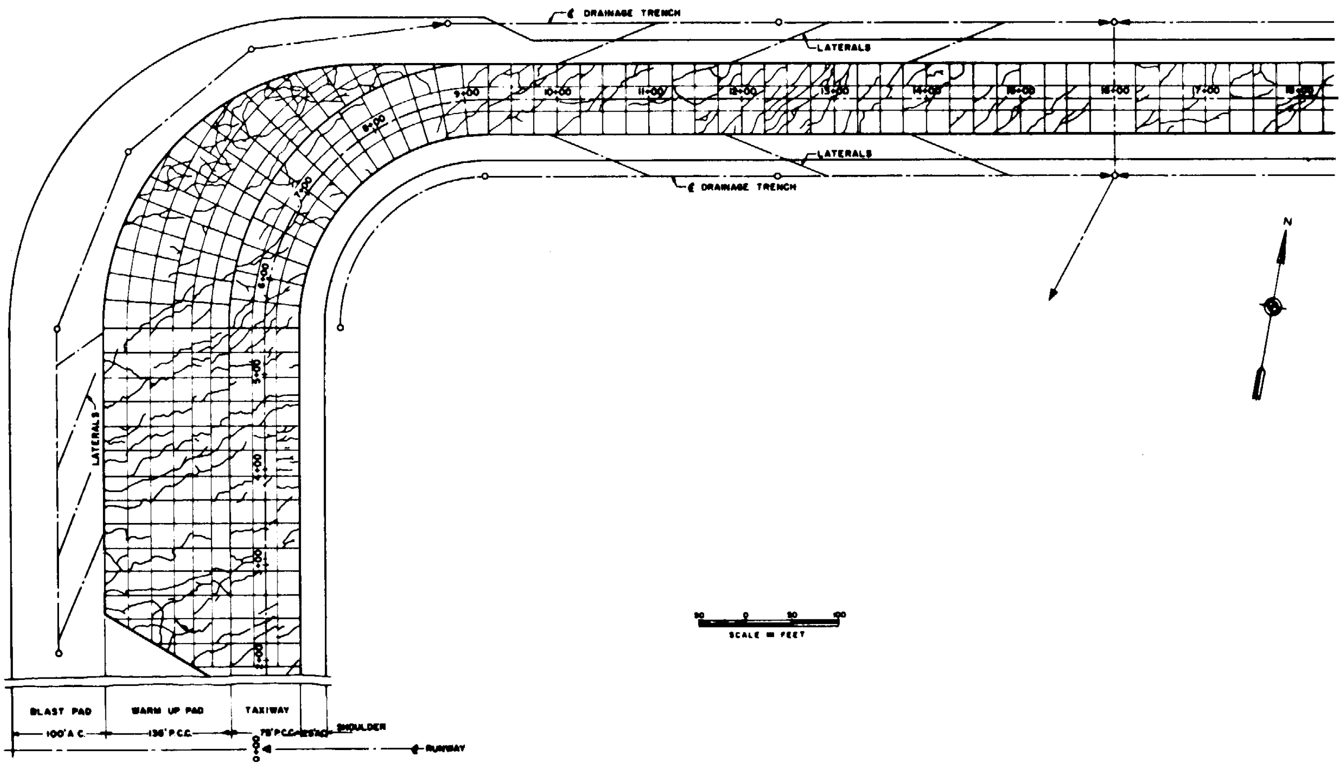

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Figure 3-8. Pattern of cracks in taxiway pavement, Elmendorf AFB, Alaska vation, and solifluction is the perceptible slow downslope flow of saturated nonfrozen soil over a base of impervious or frozen material. Creep may be frost creep, resulting from progressive effects of cyclic frost heave and settling, or may be simply extremely slow continuing deformation of frozen or unfrozen materials under stress. When siting of a facility in a location possibly susceptible to such conditions is contemplated, careful study of the terrain should be made for possible evidences of such movements. Where movement is suspected but is not obvious it may be necessary to install movement points on the slope in question and obtain actual measurements by careful surveying techniques. If either visual observation or measurements indicate a problem exists, the site should be avoided if at all possible, because stabilization or protective measures against such movements are likely to be extremely expensive or even impractical. Obvious evidences of slope instability are the bending of vegetation growth patterns out of the normal vertical position, lobe-like thrusts of material over downslope material, traces of sloughs or actual slides and displacements of roads or other facilities from their original alignments. Most such evidences are even more readily revealed by air photos than by on-the-surface inspection.

l. Other data. The availability and quality of gravel, sand, rock, water for portland cement concrete, usable local timber, and needed fill and backfill materials should be established. It is impossible to develop realistic cost estimates for the construction unless this is done.

(1) The availability of existing or potential transport facilities, means of access, sources of labor, and sources of construction equipment and supplies must be determined. These data may be controlling the decisions on type of foundation design to be employed.

(2) More detailed guidance for general site investigations is contained in TM 5-852-2/AFM 88-19, Chapter 2 [11].

(3) Design technical data in the following categories are discussed separately in the paragraphs indicated:

Soil strength tests (compression, tension, shear), paragraphs 2-5, 4-4, 4-5, 4-8
Pile load tests, paragraph 4-8
Bearing test, paragraph 4-5
Anchor tests, paragraph 4-14
Dynamic response tests (moduli, wave propagation), paragraphs 2-5, 4-6
Lateral pressures, paragraphs 4-3, 4-10

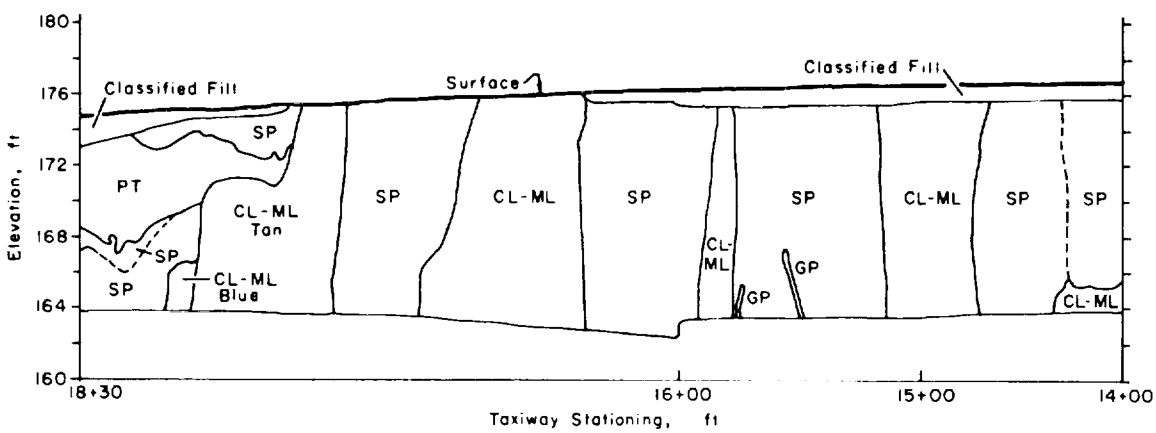

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Figure 3-9. Soil profile, south wall of trench near south edge of taxiway, Elmendorf AFB, Alaska.