GEOTECHNICAL INVESTIGATIONS FOR TRANSPORTATION FACILITIES FOUNDED IN AND CONSISTING OF EXPANSIVE CLAY SOILS

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Abstract

The cost of damage to transportation facilities as a result of them being founded in or consisting of expansive clay soils is measure in billions of dollars of repair and lost time annually. These problem soils exhibit potential to gain and lose volume differentially and without regard to loading, such that facilities are often unusable without significant remedial action. Proper project geotechnical investigations and subsequent proper construction or remedial techniques are key to appropriated project life.

This paper includes a synopsis of currently accepted practices for boring and sampling these problem soils for planning, design development, construction and maintenance. In addition, the applications of appropriate standard testing methods to samples obtained are discussed. Follow on field testing and monitoring for construction are covered.

The potential use of geophysical survey methodologies, which may be applied to geotechnical investigations of expansive clay soils, is discussed. The use of geophysical survey information, correlated with currently utilized information, to augment and more beneficially define subgrade behavior, is covered.

The conclusions include synopses of current practice methodologies and possible geophysical survey methodologies which may be used to best define expansive clay soil subgrade behavior and lead to best alternative designs, construction and remedial actions.

Introduction

It has been estimated that the amount of damage caused to facilities of all types by expansive clay soils, each year, exceeds that caused by all other natural events, such as earthquakes and floods. The amount is climbing each year and totals over 10 billion dollars annually, by estimates. A large portion of this damage affects transportation facilities. As shown in the AASHTO Manual of Subsurface Investigations, all of the states in the nation have occurrences of these soils. However, their affect on transportation facilities is most felt in areas where the combination of clay types and climate cause significant volume change potential. Significant volume change has been noted where there was as little as 10 to 15% clay present and can be the most problem where relatively pure clays exist. The clays that represent the most potential problems include, from most damaging potential to least, Smectite, Illite and Chlorite.

The purposes of this paper are several. The first is to provide sufficient background on the properties of expansive clay soils so that an understanding of how to plan and conduct a geotechnical investigation can be communicated. The second is to discuss the necessary minimum information that should be gathered during an investigation and how to plan to develop this information. The third is to cover the benefits of augmenting the investigation with geophysical survey data. The final is to present a synthesis of philosophy and standard practice which, when applied, will result in acceptable risk for those involved in the project.

The purpose of a geotechnical investigation is fact finding to support the process of analysis and design, no matter what the project situation. In particular, the facts to be found relate to earth materials which will influence and interface with or become part of the project under consideration.

Transportation facilities are of such diversity that projects, which involve parts or all of them for purposes of feasibility studies, new construction, remedial corrections and maintenance, can include practically all kinds of construction attempted for civil works. These include, in part, slopes, cuts, fills, tunnels, pavements, bridges, bridge approaches, retaining walls and buildings for roadways. The listing becomes even larger when airports are added, with their parking facilities, aprons, taxiways and runways. In addition, railroad track systems, crossings, control structures and other supporting elements add to the listing. Finally, there are those associated with water transport such as docks, wharves, channels and other water control devices. With the possible exception of high-rise buildings, transportation projects include all types of constructed works.

The process followed for geotechnical investigations, although project-type specific, is well established and utilized by geotechnical engineers. The basis for engineering design, which will utilize the information obtained, is management of the risk of some kind of failure with the level of funding needed to prevent that failure. Although not absolutely true, it is possible in almost all cases to expend enough funding on information gathering and construction to essentially eliminate failure. The problem is that the level of funding to absolutely prevent failure is not practical or available for almost all transportation projects. Therefore, it is up to those engineers involved to manage the risk to acceptable levels and provide a failure safe and economical project.

The definition of a failure for a transportation facility includes far more than a materials strength failure of some sort. Displacement of part or all of the facility, when excessive, will constitute a failure. Cracking and buckling of pavements systems can render them useless. Erosion of materials either supporting or constituting parts of a transportation facility may eventually close the facility. The key to proper performance in the case of a lock and dam or channel may be that they be able to hold water. Whatever the definition of failure, the level of risk of that failure must be managed to the point that the facility be useful throughout it's design life, or far beyond since many are used indefinitely. Only with sufficient information about the materials to be used for construction is it possible to predict their behavior as utilized and thereby effect a design which will meet expectations.

It is well recognized that the variance and diversity of earth materials far exceed those of any other type. In addition, within the limits of a specific project the variance of properties and locations of earth materials types can be significant. It is imperative, therefore, that sufficient information be made available about these materials, from field and laboratory studies, to predict their behavior in such a way as to reduce the risks taken to acceptable levels. It is not possible to sample and test all materials that affect the project, or, in most cases, provide materials of known behavior, so that the performance and life of the project depend on the geotechnical investigation. Because of this it is recommended that those selected to conduct such investigations be chosen using Quality Based Selection procedures.

While there are those entities which own transportation facilities which continue to conduct geotechnical investigations, many have or are in the process of moving to out sourcing these services to be done. This means that the processes and methodologies used are those of the general engineering community, not those followed, necessarily, by the owners' investigating personnel. In both cases, in house and out sourced, the investigations must comply with the standard of care utilized for the local in which the project exists. For this reason the guidelines given by most publications are flexible and should not be taken as more than the least investigation needed.

As will be seen the major damage causing situation for transportation facilities founded in or made of expansive clay soils is volume changes that occur when the material's moisture content changes. The resulting total and differential deflections that happen, both horizontally and vertically, are well recognized as the major damaging effect. However, loss of strength associated with cyclic shrink-swell and moisture increases has lead to many failures as well.

Available Publications

Considering the experience level of readers and the availability of information in many forms, the author chooses to provide a listing of the most prominent and modern publications found available on this subject. This listing is considered to include the most applicable found using Web search and library search techniques. The organizations whose members are most active in setting standards for transportation facilities include AASHTO, the Transportation Research Board, ASCE, ASTM and ASFE. In addition, agencies such as departments of transportation and the U.S. Army Corps of Engineers have standards. There are available, also, reference texts on the subject. Listings of applicable publications are available at the end of this paper.

The author has decided to provide the listing given because of the reality of standard of care practice varying from agency to agency, and especially between economic and geologic regions. The following discussion will provide a general overview of what is believed minimal for adequate fact gathering.

Background

Expansive clay soils are made up of from 10% to nearly 100% clay minerals which are, when sufficiently dry, physico-chemically deficient. Because of the particular clay mineral structure they are negatively charged. In order to offset this negative charge nature provides positively charged cations and water molecules, which act nearly as bipolar magnets. In addition, cations attract to themselves water molecules. The relative number of cations and water molecules which are needed to make the clay sufficiently neutral can be determined by determining it's Cation Exchange Capacity (CEC). Smectite days have very large CEC's (as high as 150 milliequivalents per 100 grams of soil), while Illite and Chlorite clays have moderate ones and Kaoline clays have relatively small CEC's (such as 40 milliequivalents per 100 grams of soil).

Another factor that contributes to the overall behavior of a clay type is it's specific surface area. This is measured in square meters of area for a gram of the clay. Kaolinite may have a specific surface area of 20 square meters per gram, while Smectite can have as high a specific surface area as 120 square meters per gram. A large specific surface area allows for very complete clay-water-cation interaction.

The type of cation associated with a clay mineral can have a large affect on its behavior. Those that contain primarily Sodium in their Exchange Complex have the potential for the largest physico-chemical need for water, while those with bivalent cations, such as Calcium, can have very low physico-chemical needs for water. A Sodium saturated clay may have a Liquid Limit well over 100 percent, and the same clay that is Calcium saturated may have a Liquid Limit of 30 or less. The use the Plastic Index (PI) to indicate the relative physico-chemical need of clay soils is prevalent. A sodium-saturated clay may have a PI of 80, while the same material calcium saturated may have a PI below 10, and may have a zero PI. Other cations have potential physico-chemical needs for water not as high as Sodium or even lower than Calcium.

The final factor internal to the material that affects volume change potential is the percent clay in the soil. Volume change is fairly directly proportional to the percent clay present. The four material factors affecting clay behavior are the percent clay, the clay mineral type and specific surface area, and the type and concentration of cations associated with the soil.

The amount of volume change that occurs in the soil subgrade is directly related to the amount of moisture change that happens. In natural situations, most materials can dry to water contents below the actual point where volume reduction stops. The measured Shrinkage Limit is the saturation water content at this volume; therefore, naturally shrunken soils will exhibit water contents below the Shrinkage Limit. Under extreme conditions their water contents can be less than 5%, but many times these values are in the lower teens of water content percentages. Empirically, it has been generally established that the highest natural water content of a subgrade where swelling stops is the Plastic Limit plus a few percent. It is possible, therefore, in natural situations that a relatively dry clay soil with a high swell potential can exhibit high swell, and no shrinkage, or at water contents slightly over the Plastic Limit can display no swell potential and have relatively large shrinkage potential. The water content at which the subgrade either starts to take on water and swell, or loose water and shrink, will determine the kind of damage potential which exists. There have been cases of shrinkage of clay soils that cause cracks large enough in the soil that a person can fall into them while walking across a subgrade with high grass on it. On the other hand, there have been cases where the ground surface has heaved in excess of 18 inches as these types of materials have swelled.

Shrinking of subgrades containing these problem soils invariably is not uniform, since the moisture changes that occur are not uniform, either horizontally or with depth. Shrinkage will lead to differentials that can easily be confused with settlement. Shrinkage is actually a loss of support or subsidence mechanism, while settlement is caused by load increase. Expansive clay subgrades can settle, however, under increases of load and, for this analysis, must be considered in the same way as any other compressible soil. This discussion will center on the effects due to the clay phenomena of shrinkage and swelling only. Shrinkage is believed to be caused by the loss of moisture that would, if held, prevent compression in the soil voids, (a sort of reverse swell). It is further activated in the most part by capillary forces as water leaves the soil interconnected pores and forms menisci pulling in on the soil structure. This process can be so strong in some cases that this process alone significantly over consolidates the materials. Differentiation of shrinkage from settlement can be made by determining if moisture was driven out by load increase or load increase occurred because of moisture loss and capillary action.

The potential reaction of an expansive clay soil during moisture change is determined by what has been discussed above, but is in reality very much affected by applied stresses, geologic stress history of the material, material denseness and permeability, and the amount of moisture change which will occur. The availability of moisture and the distance, over which it must travel to get to the particular soil, both horizontally and vertically, determine the potential change that can happen. Differences in potential energy of moisture and the clay soils involved will dictate whether moisture will move at all.

Moisture can move in expansive clay soils, as in all types of soils, as it is pushed by differential hydraulic pressures, or positive potential energies. The quantity of water moved by this method is highly dependent on the soil's interconnected void structure. The ease with which this occurs is represented by permeability. Often, however, expansive clays do not have very good interconnected voids of sufficient size to allow easy flow of moisture under hydraulic head differentials. The cracks that occur because of shrinkage are soon swelled shut upon wetting and whatever natural crack and fissure system the soil has is also swelled shut. This mechanism, therefore, plays a minor role in moisture movement in these clays.

The major mover of moisture from one place to another in an expansive clay soil is differential physico-chemical need, which may be considered a type of potential energy. These physico-chemical needs express themselves as a negative potential energy, which is often described as soil suction. Soil suction is split into two parts, that caused by the physico-chemical need of cations in soil pores and that caused by the physico-chemical need of the clay mineral present, with it's associated cations. The former is known as total suction and the later as matric suction. Although, matric suction is the stronger of the two and the actual force which pulls water molecules into the clay structure, causing the vast majority of swell potential, total suction is what moves moisture in these clay subgrades. A potential energy of zero can be visualized as that at the surface of an open body of water, while a positive potential energy in water is that occurring below the surface of a body of water, be it above or below ground. Negative potential energy, which soil suction represents, occurs above the surface of the water table in the ground or where there is no water table.

The differential of potential energy in the moisture system is what causes moisture to move in nature where a balanced or equilibrated moisture system is what is desired. The rate and amount of moisture that moves are dependent on the gradient of the differential and the difficulty of moving the moisture to cause equilibration. This gradient is the potential energy difference divided by the distance which must be transversed, while the difficulty has to do with the interconnected void system and the torturous path the moisture molecules must follow. For example, denser soil structure configurations tend to be harder to penetrate, but will open more as swell occurs, easing the transfer of moisture.

Geologic stress history is an important factor affecting volume change potential in expansive clay soils. A soil which has been compressed enough to be a shale has high potential to swell as moisture is allowed to get to the clay, however, the movement of moisture into these materials is restricted. In addition, as a result of the long term compression, shales may have diagenetic bonds form between clay mineral stacks that restrict their swelling for a significant period of time during the weathering process. The difficulty comes in predicting, using normal test methods, how these soils will behave over the design life of a project. It can be said that, generally, the more stress history an expansive clay soil has the more swelling potential it has and the less shrinkage potential it has. Since natural project soils of this type will undergo many cycles of wetting and drying, and have a release of their diagenetic bonds over the project design life, the key to prediction of behavior is proper sampling, pretesting preparation and testing methodologies.

Just as in the case of over consolidation, subgrade denseness has an effect on swell and shrinkage potential. Simply put, this is that the denser a soil of this type is, the higher it's swell potential (all other factors unchanged) and the lower it's shrinkage potential. Although denseness has a large affect on volume change potential, it is only practically controllable during remolding and compaction of subgrade soils.

While controlling of shrinkage is not practical by manipulating loads on the subgrade, the application of loads can greatly affect swell potential. Generally speaking, increases of overburden loads and/or project loads on a subgrade may be able to overcome the swelling pressure exerted by the clay soil as it takes on moisture. This is especially true for subgrades which have small or moderate swell pressure potentials. In addition, an increase in such loads will reduce the swelling potential in all cases. The key is the relationship of the applied overburden pressure to the swelling pressure potential of the soil at the initial moisture content and denseness expected in the project situation.

The complexity of expansive clay soil behavior is added to by the natural moisture differentials that happen in subgrades. The amount of water content change, gain and loss, which occurs is dependent on the climatic cycle happening during the change, i.e. a longer drought, higher temperatures or winds will cause more drying, while a longer rainfall period, with higher humidity and less wind will allow for more moisture increase. As long as the rainfall is enough to provide a source of water at the ground surface for soil in take, the rate of rainfall does not appear to matter. Studies done by ponding water versus sprinkling indicate that both cause the same rate of soil moisture in take. The longer a period of drought or rainfall, the deeper the effects of moisture loss or gain can extend.

Depths to which drought can reduce moisture contents over time are determined by climatic conditions. The deepest penetrations would be in arid areas, while the least in tropical areas. Examples of these are a depth of drying or changing moisture content in St. Louis of 7 or 8 feet, and a depth of up to 15 feet in the Dallas area. What this means is that moisture levels in the clays in these areas can fluctuate to these levels at least on a yearly basis. Soils located in these depths of moisture change are those associated with at least annual volume change behavior and are said to be in the active zone. The amount of moisture change is greatest at the soil subgrade surface and decreases with depth to zero at the bottom of the active layer. These are the materials that can be expected to shrink and provide lessening support during times of drought, if measures are not taken to prevent this behavior. These are the materials that can be expected to swell during the life of the project and their swelling behavior must be predicted or modified so as to not affect the project.

Over a long period of time, and depending on geologic history, shale materials can be expected to be at moisture contents well below those that will satisfy their physico-chemical need. Natural weathering processes will not eventually provide to them the moisture to satisfy these needs. However, improper handling of moisture occurring in a project situation can sometimes lead to wetting of these deeper and drier materials, causing deep-seated heave. These deep-seated swelling situations have lead to movements of the ground surface of 2 feet upward, and have been known to have the capability to shear structural grade, well reinforced, concrete grade beams of large size into two pieces.

The amount of movement affecting a transportation project caused by expansive clay soils is dependent on the depth of these materials over rock or other materials that are not expansive. As indicated above, movement is actuated by expansive clay soils that change moisture levels and the amount of movement is directly related to the depth of these clays that change moisture levels. It is further affected by the moisture level from which the change starts and how much it changes, their stress history, their denseness and the overburden stress on them during the process of moisture change. The rate at which this change of moisture and related movement occur depends largely on the differential gradient of their potential energy relative to that of the source of moisture or source of drying.

Since studies of clay mineralogy and soil chemistry are relatively impractical for most geotechnical investigations, prediction of expansive clay soil behavior must be based on properties that are normally determined. These, coupled with an understanding of geologic history of these materials, are essential to complete analyses. It important to develop a profile of the level and variance of pertinent properties of the subgrade, including Atterberg Limits, swelling behavior, shrinkage behavior, water contents, dry unit weights and, if possible, total suction. These will allow determination of the nature of the materials present and how they vary, and how they can behave under worse case project situations. It is equally important to test enough relatively undisturbed samples for shear strength under worse case scenarios. Of particular importance is the use of saturated, drained, residual testing to determine shear strength for slope designs. This is most effectively done utilizing direct shear test methods. Development of predictions of swell is best done using locally accepted methods and procedures, approved for the transportation agency or company involved, since these vary considerably and are many in number.

There are practical and economical methods to modify the behavior of expansive clay soils, so that they can be treated without consideration for volume change caused by moisture changes. Some of these methods also result in a material that has superior shear strength, less compressibility and improved durability to weathering. Sampling and testing for applications of these methods of improvement require additional planning and result in a broader scope than for normal situations. The benefits derived by the use of these improvement methods far outweigh the cost associated with testing required for their proper use.

The first alternative that may be explored is the removal of all expansive clay and replacement of it with suitable materials that will not exhibit shrink-swell behavior. The second, similar, method is removal of enough expansive clay soil to reduce the problematic behavior of the subgrade to acceptable levels, and replacement with suitable materials. Both of these methods require knowledge of the depth and activity of subgrade soils, so that the depth or removed clay can be determine. The material which will be used to replace the clay must also be tested for compaction characteristics and remolded properties used for design.

The third, and least used method, is to build the project so that it, in a sense, bridges over the expansive clay soils. An example of this is a bridge bent built on drilled shafts which extend well below the active layer, are underreamed and reinforced against pullout by expanding near-surface soils, and that has between it and the expansive subgrade an airspace such that swelling soils cannot affect it. To use this method knowledge of the depth of the active layer and predicted vertical rise (PVR) must be known, in addition to the information detailed above.

Since removing and replacing expansive clay soil with more permeable materials, resulting in a danger of wetting deeper expansive clays and causing deep-seated heave, and bridging of the clays is usually too costly, the vast majority of improvement techniques involve changing the behavior of the clay in place or as remolded in fills. These methods can be broken into three possible categories: mechanical reworking of the clay soil, addition of agents to modify their behavior, and addition of agents to bind clay particles together and seal them from moisture change.

Mechanical methods include limiting dry unit weights within acceptable ranges to reduce swelling and control of moisture contents. Compaction at standard levels of energy and limiting the resultant dry unit weights to between 90 and 95% of the maximum achievable will usually provide the strength and compressibility needed and dramatically reduce swelling potential over that which occurs when the upper percent of maximum dry unit weight is not specified. Compaction of these clays at moisture levels between the optimum for compaction and four percent moisture above the optimum will result in a subgrade that will have acceptable swelling behavior, if not allowed to dry out from this level.

Water content control can limit the movements expressed by these clays, since moisture change is what causes their volume change. It is nearly impossible to prevent them from moisture, so the water content control method includes prewetting them to what satisfies their physico-chemical need, and providing devices or methods to keep them at this water content for the project design life. Injection of water has been successfully applied to assist in this effort and vertical moisture movement barriers (geomembranes) have been applied in successful moisture stabilization. Determination of the target moisture content and measuring when it is achieved in the field are needed to apply this method.

The application of chemical agents to modify expansive clay soil behavior could be the subject of more than one conference. This is also true to a lesser extent for agents used to bind and seal these clays to improve behavior. It is important, here, to include the philosophy of testing for these agents. Changes to Atterberg limits are often used to determine if an agent will work to improve these clays, but this is not a guarantee that improvement will or will not occur. The best testing to use in every case is a performance test, of which swelling tests are an example, which places the improved soil in the field situation, using field gradation requirements and large specimens to test for the improvement(s) wanted. These test regimens must include testing of control situations, as well as those where agents have been applied. The two control situations that must be utilized, at a minimum, are those of the soil as unmodified and the soil as modified with as much water as will be added along with the agent. Comparison of results using these control situations with the results using the agent will provide knowledge of what addition of the agent has done to improve clay behavior. What is called stabilization, or binding of grains, etc, can be tested in the same way, using tests which, again, determine the desired improvements of performance.

One thought should become obvious but must usually be stated. Expansive clay soils can be dealt with and their problematic behaviors overcome by proper investigation techniques, proper construction techniques and proper maintenance.

The Investigation Process

In many ways the geotechnical investigation process used for expansive clay soil subgrades is as utilized for general purposes and non-seismic conditions, similar to what is provided in papers elsewhere in these proceedings. The depth and number of borings is essentially the same as for exploring any other cohesive soil subgrade and the equipment used is the same. The use of continuous push thin walled samplers is prevalent for these materials, since a profile of the properties outlined above is needed and many of these come from testing relatively undisturbed samples. In addition, the materials, which cause the most problems for projects, are near surface clays, which can be sampled in this manner easily. The scope of geotechnical investigations, including boring, sampling and testing, for these kinds of subgrades is very much local dependent, since these materials vary between locals and since climatic conditions are local specific. Understanding the local standard of care in practice is essential to an adequate investigation.

The minimum information needed to have a complete investigation of an expansive clay subgrade is that to develop its behavior patterns and to predict its specific behavior starting at the time of construction. This is where the problems occur, since investigations take place well before construction and during the intervening time crucial subgrade properties have changed. Those that change because of climatic changes happen in the near surface materials, which are the most critical to behavior and the project for which the study is being made. Therefore, investigations must be timed to as close as possible coincide with construction.

It is necessary to develop a subgrade profile of critical properties, such as water content, dry unit weight, Atterberg Limits and Linear shrinkage (or some form of measurement of shrinkage potential), and soil suction (if possible). Swelling tests are also needed to determine the full extent of swell potential in the form of amount of swell and swelling pressures. Research has shown that individual test specimens must be used for each test and that combined swell pressure testing followed by volume change will not tell the true nature of the second behavior tested. Some agencies and firms, such as the U.S. Army Corps of Engineers, have methods that appear to be combined but actually trace the field stress history and result in valuable information on swell potentials. As would be expected, research has shown that taking a relatively undisturbed sample out of it's natural stress environment dramatically affects the swell potentials that will be determined from any test. Therefore, a test that puts the specimen back into the natural stress environment before testing for swell upon saturation will result in the best measurement of swell potential.

Testing is also conducted for shear strength and compressibility, in the form of consolidation, etc, since the loads that will be applied may exceed swelling potentials of the soil and may cause shear failures to occur. A very prevalent type of failure in these materials occurs in slopes where the soil going through cycles of shrink and swell will soften and become higher in moisture content during times of wetting. The net result is a material that has lessened in strength to its residual shear strength. If the slope is designed for the undrained peak shear strength of the soil or even the drained peak shear strength, it will eventually fail. Therefore, direct shear testing to determine the saturated drained residual shear strength must be done to provide the residual friction angle for use in safe slope design. Other strength tests, appropriate for the loading situation, are normally used for information for design of foundation systems and retaining structures.

Using the results of testing outlined above and locally utilized theories, the potential vertical rise (PVR) is calculated. Currently, there are several methodologies used worldwide for this calculation. It is important to utilize that methodology either approved by the agency involved or that follows the local standard of care practice. The PVR is used to estimate the amount of space to leave under structural systems that should not be affected by swelling soils and to design slabs-on-grade when predicting forces, moments and movements of the slabs.

Modification or stabilization of expansive clays is often done to reduce the potential for damage to transportation projects. One of the most cost-effective measures is water content stabilization. In order to accomplish this, a target moisture content is needed and the investigation will include developing this information using Atterberg Limits, soil suction results or swelling test results. Compaction is normally done so as to limit the developed dry unit weight to a range acceptable for both strength and reduced swell potential. In addition, the compacted water content is limited to values above the optimum for maximum dry unit weight. Therefore, the investigation must include determination of strength and swelling potential for compacted soils, varying dry unit weight and water content. Most often, however, the acceptable values have been developed and are part of the local standard practice.

An investigation that includes determination of the optimum types and levels of chemical agents for the purpose of modifying and/or stabilizing these problem soils can be very extensive. Locally experience with the use of these agents will assist the investigator in reducing the amount of testing needed. It is important to note that falling into the trap of always using the same agent(s) can lead to less than optimal results and economics of projects. Therefore, the investigator must strive to keep in touch with what is available and feasible, and should continue to seek knowledge concerning these. The amount of sampling needed for modification or stabilization testing is not out of the ordinary for that needed for general investigations, except that the quantities of disturbed materials that will be treated need to be much larger. The testing required for these treated soils should be that which will put the them into field simulated performance tests. The specimens should be prepared as the subgrade would be, treated with the agents in the same way as the field, pulverized to only the extent they would be in the field, compacted to the field standards to be used and cured as in the field before testing starts. The use of finely pulverized soils, such as used for determination of Atterberg Limits, and those pulverized for compaction tests will lead to improper results when compared to those done at field specification pulverization.

The proper geotechnical investigation on expansive clay soils will provide predictions of behavior for the situation when construction begins and offer alternatives for dealing with these problematic soils. These alternatives often include modification and/or stabilization of the subgrade soils. The program of sampling and testing must address these issues.

The sum result of geotechnical investigations conducted without the use of geophysical survey methods is a document containing the probable location, vertically and horizontally, of earth materials based on fairly widely spaced columns or excavated volumes of these materials. Each individual having much experience at all can relate how much remains unknown about the materials that will actually be involved in the project. There are the stories of how a filled-in stream was encountered which was unknown, or how the top of rock was so erratic in a limestone residual material that it was either missed altogether or was there near the surface in borings but no where else. These, among the many other examples, support the use of geophysical survey methods to reduce the unknowns and thereby reduce the risks taken.

Geophysical Survey Methodologies

Geophysical techniques applied to geotechnical investigations can be characterized the two general groups: investigations conducted from ground surface and those conducted in boreholes. Each group is further separated in the two basic modes of data generation, those using measurement of existing earth fields and those using measurement of fields induced deliberately for the purpose of the investigation. Investigations conducted from ground surface typically provide information about the subsurface both laterally and to some depth, while most of the borehole investigations, with some exceptions, provide detailed information about materials only in the intermediate vicinity of the borehole are between boreholes. The testing energy fields and the induced energy fields pertinent to two test hole investigations include:

Existing Fields (Passive)	Induced Fields (Active)
Gravimetric	Seismic
Electric	Acoustic
Magnetic	Electric
Thermometric	Electromagnetic
Nuclear	Nuclear
	Ground Penetrating Radar (GPR)

Interest in existing energy fields occurs because the strength of the field of any particular point can reflect the geological conditions present between that point in the source of the field. Measurements of existing geophysical fields and resulting interpretations range from detailed gravimetric plan maps showing relative depth of bedrock, to the identification of zones and flow rates of moving groundwater penetrated by boreholes. In each case, the density of surface observation stations or frequency of borehole recording or measurement points establishes the resolution level of the data collected.

Geophysical methods that rely upon the reaction of subsurface materials to energy introduced by some deliberate process are typically much more versatile for geotechnical purposes. The appropriate equipment can be selected, the locations for investigation chosen, and parameters measured in accordance with the specific project requirements, provided that the measurements are within the ability of the geophysical techniques to be applied. Selection of the method or methods appropriate to measure or derive needed parameters must be based on knowledge of how the resulting data are to be used, and how the data should not be used.

The induced fields of geophysical techniques are more widely used than passive techniques. Joint use of both induced and existing Fields is common in some types of investigations. Selection of the method used in the induced case can be based upon the need for depth of coverage, in the case of traditional seismic and GPR seismic, electrical, or electromagnetic studies, versus the specific type of information needed as in seismic, acoustic, nuclear or electrical studies. Resolution capability is also selectable to some degree, with resolution increasing as the density of observation points or rate of observation is increased. The following table indicates which geophysical methods can be used to investigate geologic conditions that may be important in the signing of transportation facilities. An understanding of limitations of these methods is essential to understand their actual usefulness.

The data derived from geophysical investigations usually have to be interpreted by experienced geophysical analysts prior to use by engineering geologist by geotechnical engineers. In all but a few applications, such as reconnaissance investigations for example, the results of geophysical investigations should always be supported by direct observation of subsurface conditions by means of borings, tests pits, trenches, outcrops and other geological information. In this way geophysical data augment that found using these methods to assist in explaining what lies between other sampling sites.

Geophysics Applied to Investigations for Transportation

Conditions to be Investigated	Useful Geophysical Techniques	
	Surface	Subsurface
Depth of Stratified Rock and Soil	Seismic Refraction GPR	Borehole Logging
Depth to Bedrock	Seismic Refraction, GPR, Electric Resistivity	Borehole Logging
Depth to Groundwater Table	Seismic Refraction, GPR Electric Resistivity	
Location of Highly Fractured Rock And /or Fault Zones	Electric Resistivity	Borehole TV Camera
Bedrock Topography	Seismic Refraction, Gravity, GPR	
Locations of Planar Igneous Intrusions	Gravity, Magnetics, Seismic Refraction, GPR	
Solution Cavities	Electric Resistivity, Gravity, GPR	Borehole TV Camera
Isolated Pods of Sand, Gravel, Or Organic Material	Electric Resistivity	Borehole Logging
Permeable Rock and Soil Units	Electric Resistivity	Borehole Logging
Topography of Lake, Bay, or River Bottoms	Seismic Reflection (Acoustic Soundings), Side-Scan Sonar	
Topography of Lake, Bay, or River Bottom Sediments	Seismic Reflection (Acoustic Soundings)	
Lateral Changes in Lithology of Rock and Soil Units	Seismic Refraction, Electrical Resistivity, GPR	

The use of geophysical survey methods during a geotechnical investigation has the potential to enhance the total knowledge of project earth materials. When properly applied, by experienced and knowledgeable people, and when their strengths and limitations are taken into account, the results provided by these methods can significantly reduce the risks taken during design and construction of facilities.

Summary and Conclusions

This report includes a general discussion of geotechnical investigations for expansive clay soils, their planning and conduct. Emphasis has been placed on the understanding and reduction of risks associated with utilizing the limited information available from these investigations. In lieu of a bibliography, a listing of available references and organizations where information is available are given. The general review of standard practice is based on the reference materials available and the author's experience with investigations in Missouri, Texas and Oklahoma, and is not meant to be an exhaustive coverage of all local practices. The introduction of geophysical survey methods is a general overview.

The purpose of geotechnical investigations as part of the planning, design and construction of transportation facilities is to provide information about earth materials that will affect the project and enable prediction of their behavior. The amount of risk of failure and damage related to expansive clay soil behavior taken during the design, construction and operation of these facilities is indirectly proportional to the extent of the knowledge available about these materials. A balance between necessary levels of knowledge and the cost of obtaining that knowledge must include consideration of the risks involved and the inherent variability of expansive clay soils. The use of geophysical survey methods, in conjunction with a well planned drilling, sampling and testing program can significantly and economically reduce the risks that are ultimately taken.

Applicable Publications

Publications available from AASHTO:

Manual on Subsurface Investigations, 1988.

Interim Specifications and Methods of Sampling and Testing, Adopted by the AASHTO Subcommittee on Materials, 1989.

Publications available from ASCE:

Foundation Engineering: Current Principles and Practices: Proceedings of the Congress, Evanston, Illinois, June 25-29, 1989, Edited by Fred H. Kulhawy, Geotechnical Division, ASCE, 1989.

Advances in Site Investigation Practice, C. Craig, ASCE, 1996, 958 pages.

Soil Sampling, Technical Engineering and Design Guides as Adapted from the U.S. Army Corps of Engineers, No. 30, ASCE, 2000, 224 pages.

Unsaturated Soils, Geotechnical Special Publication No. 39, Sandra L. Houston and Warren K. Wray, Proceedings of the ASCE Convention, Dallas, Texas, 1993. 224 pages.

Publications available from ASFE and ASTM:

Members of ASFE can receive publications on this subject by contacting ASFE. Non-members can purchase publications on this subject.

Members of ASTM can purchase at reduced cost standards for testing earth materials by contacting ASTM. Non-members can purchase these standards also.

Recently published reference texts:

Geotechnical Engineering Investigation Manual, Roy E. Hunt, Mc Graw-Hill, 1984, 983 pages.

Expansive Soils, Problems and Practice in Foundation and Pavement Engineering, John D. Nelson and Debora J. Miller, John Wiley and Sons, Inc., 1992, 259 pages.

Foundations in Problem Soils, A Guide to Lightly Loaded Foundation Construction for Challenging Soil and Site Conditions, Steven J. Greenfield and C.K. Shen, Edited by S. Scot Litke of ADSC, Prentice Hall, 1992, 240 pages.

Fundamentals of Soil Behavior, Second Edition, James K. Mitchell, John Wiley and Sons, Inc., 1993, 437 pages.

Soil Mechanics for Unsaturated Soils, D. G. Fredlund and H. Rahardjo, John Wiley and Sons, Inc., 1993, 517 pages.

Geomembranes and the Control of Expansive Soils in Construction, Malcolm Steinberg, McGraw-Hill, 1998, 222 pages.