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Role of Geotechnical Properties of Soil on Civil Engineering Structures

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Abstract The occurrence and distribution of soils in nature varies from location to location. The type of soil depends on the rock type, its mineral constituents and the climatic regime of the area. Soils are used as construction materials or the civil engineering structures are founded in or on the surface of the earth. Geotechnical properties of soils influence the stability of civil engineering structures. Most of the geotechnical properties of soils influence to each other. In this paper, different geotechnical properties of soils such as specific gravity, density index, consistency limits, particle size analysis, compaction, consolidation, permeability and shear strength and their interactions and applications for the purpose of civil engineering structures have been discussed.

Keywords Geotechnical Properties, Civil Engineering Structures, Soil Particle, Shear Strength, Bearing Capacity of Soil

1. Introduction

The civil engineering structures like building, bridge, highway, tunnel, dam, tower, etc. are founded below or on the surface of the earth. For their stability, suitable foundation soil is required. To check the suitability of soil to be used as foundation or as construction materials, its properties are required to be assessed [1]. As per different researchers [2, 3], assessment of geotechnical properties of subsoil at project site is necessary for generating relevant input data for design and construction of foundations for the proposed structures. Researchers [4-7] have stated that proper design and construction of civil engineering structures prevent an adverse environmental impact or structural failure or post construction problems.

Information about the surface and sub-surface features is essential for the design of structures and for planning construction techniques. When buildings impose very heavy loads and the zone of influence is very deep, it would be desirable to invest some amount on sub-surface exploration than to overdesign the building and make it costlier. For complex projects involving heavy structures, such as bridges, dams, multi-storey buildings, it is essential to have detail exploration. The purpose of detailed explorations is to determine the engineering properties of the soils for different strata [8].

When the foundations of any structure are constructed on compressible soil, it leads to settlement. Knowledge of the rate at which the compression of the soil takes place is essential from design consideration. The properties of the soil such as plasticity, compressibility or strength of the soil always affect the design in the construction. Lack of understanding of the properties of the soil can lead to the construction errors. The suitability of soil for a particular use should be determined based on its engineering characteristics and not on visual inspection or apparent similarity to other soils. The loading capability of soil depends upon the type of soil. Generally, fine grained soils have a relative smaller capacity in bearing of load than the coarser grained soils [9].

Plasticity index and liquid limit are the important factors that help an engineer to understand the consistency or plasticity of clay. Though shearing strength constants at liquid limits but varies for plastic limits for all clays [10]. Permeability influences the civil engineering structures. As per Karsten et al. [11], the shear strength of soils is of special relevance among geotechnical soil properties because it is one of the essential parameters for analyzing and solving stability problems (calculating earth pressure, the bearing capacity of footings and foundations, slope stability or stability of embankments and earth dams). Considering these, interactions among different geotechnical properties and their influences on civil engineering structures have been discussed in this paper.

2. Geotechnical Properties of Soils

Different geotechnical property of soils has different influence on the civil engineering structures. They also depends upon each other. The properties are discussed as under:

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2.1. Specific Gravity

Specific gravity is the ratio of the mass of soil solids to the mass of an equal volume of water. It is an important index property of soils that is closely linked with mineralogy or chemical composition [12] and also reflects the history of weathering [13]. It is relatively important as far as the qualitative behavior of the soil is concerned [14] and useful in soil mineral classification, for example iron minerals have a larger value of specific gravity than silicas [15]. It gives an idea about suitability of the soil as a construction material; higher value of specific gravity gives more strength for roads and foundations. It is also used in calculation of void ratio, porosity, degree of saturation and other soil parameters [16]. Typical values of specific gravity are given in Table 1.

Table 1. Typical values of specific gravity (Bowles, 2012)

Type of soil	Specific gravity
Sand	2.65-2.67
Silty sand	2.67-2.70
Inorganic clay	2.70-2.80
Soil with mica or iron	2.75-3.00
Organic soil	1.00-2.60

Based on the study, Roy and Dass [17] found that increase in specific gravity can increase the shear strength parameters (cohesion and angle of shearing resistance). Roy [18] observed that increase in specific gravity also increases the California bearing ratio i.e. strength of the subgrade materials used in road construction.

2.2. Density Index

The degree of compaction of fine grained soils is measured in relation to maximum dry density for a certain compactive effort, like 90% of light compaction density or proctor density. But in case of coarse grained soils, a different sort of index is used for compaction. Depending upon the shape, size, and gradation of soil grains, coarse grained soils can remain in two extreme states of compaction, namely in the loosest and densest states. Any intermediate state of compaction can be compared to these two extreme states using an index called relative density or density index. The soil characteristics based on relative density are shown in Table 2 [19].

Density index is expressed in percent and is defined as the ratio of the difference between the void ratio of a cohesionless soil in the loosest state and any given void ratio to the difference between its void ratios in the loosest and the densest states [20]. It is a measure of the degree of compactness, and the stability of a stratum [14].

As per Apparao and Rao [21], relative density is an arbitrary character of sandy deposit. In real sense, it expresses the ratio of actual decrease in volume of voids in a sandy soil to the maximum possible decrease in volume of voids i.e. how far the sand under investigation can capable to the further densification beyond its natural state. Its determination is helpful in compaction of coarse grained soils and in evaluating safe bearing capacity of sandy soils.

Table 2. Characteristics of soils based on relative density

Relative density (%)	Soil compactness	Angle of shearing resistance (^{0})
0-15	Very loose	<28
15-35	Loose	28-30
35-65	Medium	30-36
65-85	Dense	36-41
85-100	Very dense	>41

2.3. Consistency Limits

The consistency of a fine-grained soil is largely influenced by the water content of the soil. A gradual decrease in water content of a fine-grained soil slurry causes the soil to pass from the liquid state to a plastic state, from the plastic state to a semi-solid state, and finally to the solid state. The water contents at these changes of state are different for different soils. The water contents that correspond to these changes of state are called the Atterberg limits. The water contents corresponding to transition from one state to the next are known as the liquid limit, the plastic limit and the shrinkage limit [19].

The liquid limit of a soil is the water content, expressed as percentage of the weight of the oven dried soil, at the boundary between the liquid and plastic states of consistency of the soil [22]. The soil has negligibly small shear strength [19]. The plastic limit of a soil is the water content, expressed as a percentage of the weight of oven dried soil, at the boundary between the plastic and semi-solid states of consistency of the soil [22].

The plastic limit for different soils has a narrow range of numerical values. Sand has no plastic stage, but very fine sand exhibits slight plasticity. The plastic limit is an important soil property. Earth roads are easily usable at this water content. Excavation work and agricultural cultivation can be carried out with the least effort with soils at the plastic limit. Soil is said to be in the plastic range when it possesses water content in between liquid limit and plastic limit. The range of the plastic state is given by the difference between liquid limit and plastic limit and is defined as the plasticity index. The plasticity index is used in soil classification and in various correlations with other soil properties as a basic soil characteristic [14]. Based on the plasticity index, the soils were classified by Atterberg, shows the correlations between the plasticity index, soil type, degree of plasticity and degree of cohesiveness (Table 3) [16].

Skempton [23] observed that the plasticity index of a soil increases linearly with the percentage of the clay-sized fraction. Laskar and Pal [1] found that plasticity depends on grain size of soil. With the increase of sand content plasticity index of soil decreases, which might be due to decrease of inter molecular attraction force. Due to decrease of attraction force, liquid limit of the soil decreases and accordingly plasticity index decreases. But as the clay content increases inter molecular attraction force increases and liquid limit increases.

Table 3. Types of soils based on plasticity index

Plasticity index (%)	Soil type	Degree of plasticity	Degree of cohesiveness
0	Sand	Non-plastic	Non-cohesive
<7	Silt	Low plastic	Partly cohesive
7-17	Silt clay	Medium plastic	Cohesive
>17	Clay	High plastic	cohesive

The shrinkage limit is the maximum water content expressed as a percentage of oven-dried weight at which any further reduction in water content will not cause a decrease in volume of the soil mass, the soil mass being prepared initially from remolded soil [24]. The finer the particles of the soil, the greater are the amount of shrinkage. Soils that contain montmorillonite clay mineral shrink more. Such soils shrink heterogeneously during summer, as a result of which cracks develop on the surface. Further, these soils imbibe more and more water during the monsoon and swell. Soils that shrink and swell are categorized as expansive soils. Indian black cotton soils belong to this group [14].

According to Prakash and Jain [16], the value of shrinkage limit is used for understanding the swelling and shrinkage properties of cohesive soils. It is used for calculating the shrinkage factors which helps in the design problems of the structures made of the soils or/and resting on soil. It gives an idea about the suitability of the soil as a construction material in foundations, roads, embankments and dams. It helps in knowing the state of given soil.

As per Ersoy et al. [25], consistency is an important property and is a useful measure for the processing of very fine clayey soils. Plasticity and cohesion reflect the soil consistency and workability of the soils. However, these properties of the soils play an essential role in many engineering projects, such as the construction of the clay core in an earth fill dam, the construction of a layer of low permeability covering a deposit of polluted material, the design of foundations, retaining walls and slab bridges, and determining the stability of the soil on a slope.

Agbede et al. [40] conducted the study at University of Ibadan (UI), Nigeria. The building under study was two storey with basement complex and housed offices, classrooms, a laboratory, library and a computer room. This building is located in a flat, low terrain with an upper layer of loose lateritic clayey soils while the underlying soil is sandy soil mixed with silty clay material. The cracks were observed due to expansive soil supporting the foundation of the building. The soil foundation contains high amount of clay with high plasticity index.

2.4. Particle Size Analysis

The percentage of different sizes of soil particles coarser than 75 μ is determined by sieve analysis whereas less than 75 μ are determined by hydrometer analysis. Based on the particle size analysis, particle size distribution curves are plotted. The particle size distribution curve (gradation curve) represents the distribution of particles of different sizes in the soil mass [26]. It gives an idea regarding the gradation of the soil i.e. it is possible to identify whether a soil is well graded or poorly graded. In mechanical soil stabilization, the main principle is to mix a few selected soils in such a proportion that a desired grain size distribution is obtained for the design mix. Hence for proportioning the selected soils, the grain size distribution of each soil is required to be known [16].

Apparao and Rao [21] explained that the grain size analysis is widely used in classification of soils. The data obtained from grain size distribution curves is used in the design of filters for earth dams and to determine suitability of soil for road construction, air fields, etc. Raj [14] stated that the particle size of sands and silts has some practical value in design of filters and in the assessment of permeability, capillarity, and frost susceptibility. Very relevant and useful information may be obtained from grain size curve such as (i) the total percentage of larger or finer particles than a given size and (ii) the uniformity or the range in grain-size distribution.

Bowles [15] found that particle-size is one of the suitability criteria of soils for roads, airfield, levee, dam, and other embankment construction. Information obtained from particle-size analysis can be used to predict soil-water movement, although permeability tests are more generally used. The susceptibility to frost action in soil, an extremely important consideration in colder climates, can be predicted from the particle-size analysis. Very fine soil particles are easily carried in suspension by percolating soil water, and under drainage systems are rapidly filled with sediments unless they are properly surrounded by a filter made of appropriately graded granular materials. The proper gradation of this filter material can be predicted from the particle-size analysis. Particle-size of the filter materials must be larger than the soil being protected so that the filter pores could permit passage of water but collect the smaller soil particles from suspension.

As per Dafalla [27], the sand shape whether rounded, subrounded, or angular will affect the shearing strength of soil. Angular grains provide more interlock and increased shear resistance. The gradation and size of the sand affect the shear resistance. Well-graded materials provide more grain to grain area contact than poorly graded materials. Porosity and spaces available for clay within the sand is an important while considering the mixtures of clays and sands.

2.5. Compaction

Soil compaction is one of the ground improvement techniques. It is a process in which by expending compactive energy on soil, the soil grains are more closely rearranged. Compaction increases the shear strength of soil and reduces its compressibility and permeability [19, 21].

Murthy [10] explained that when an earth dam is properly compacted, the shear strength of the material is increased and dam becomes more stable. Since the soil becomes dense, its permeability gets decreased. The decrease in the permeability of the dam decreases the seepage loss of the water stored. The settlement of the dam also decreases due to the increase in the density of the materials.

According to Prakash and Jain [16], compaction of soils increases the density, shear strength, bearing capacity but reduces their void ratio, porosity, permeability and settlements. The results are useful in the stability of field problems like earthen dams, embankments, roads and airfields. The moisture content at which the soils are compacted in the field is controlled by the value of optimum moisture content determined by the laboratory proctor compaction test. The compaction energy applied in the field is also controlled by the maximum dry density determined in the laboratory.

Durgunoglu et al. [42] used heavy dynamic compaction method for the compaction of foundation subsoil of Carrefoursa Hypermarket and Trade Center in Bursa, Turkey. In order to increase the bearing capacity of the foundations sub soils as well as to control the total and differential settlements underneath the foundations.

A mega water (208 MLD) supply project was undertaken by Guwahati Metropolitan Development Authority (GMDA) funded by Japan International Cooperation Agency (JICA) for central Guwahati region, India. Mechanical compaction of foundation soil using road roller were observed to be adequate for the construction of foundation [43].

2.6. Consolidation

When a soil layer is subjected to compressive stress due to construction activities, it undergoes compression. The compression is caused by rearrangement of particles, seepage of water, crushing of particles, and elastic distortions. Settlement of a structure is analyzed for three reasons: appearance of structure, utility of the structure, and damage to the structure. The aesthetic view of a structure can be spoiled due to the presence of cracks or tilt of the structure caused by settlement. Settlement caused to a structure can damage some of the utilities like cranes, drains, pumps, electrical lines etc. Further settlement can cause a structure to fail structurally and collapse. Settlement is the combination of time-independent (e.g. immediate compression) and time-dependent compression (called consolidation) [14].

According to Prakash and Jain [16], the main aim of a consolidation test is to obtain soil data which are used in predicting the rate and amount of settlement of structure founded on clay primarily due to volume change of the clay. The information obtained for foundations resting on clay are: (i) total settlement of foundation under any given load, (ii) time required for total settlement due to primary consolidation, (iii) settlement for any given time and load, (iv) time required for any percentage of total settlement or consolidation, and (v) pressure due to which soil already has been consolidated/compressed.

Abeele [28] explained that lowering of water table or dewatering is probably the best known cause of massive settlement. When submerged, soil particles are subjected to buoyancy. Upon dewatering, the buoyancy is removed and the apparent increase in pressure results in consolidation, even though there is no increase in external load. Vibrations can also have a densification effect on soils and lead to subsequent settlement. The effects can be severe when the vibration frequency matches the soil's natural frequency. Soils often fail and settle disastrously as a result of earthquakes. Devastating landslides are often one of the results of such occurrences. Of the three phases of soil, only the solid phase controls the resistance to compression and shear. Water, present in a moist soil is highly incompressible but as a liquid, is not capable of resisting shear loads. Air, present in unsaturated soils, will not support compression or shear loads.

Head [29] stated that in a saturated soil, compression will be primarily caused by expulsion of water out of the soil voids. Under the influence of an externally applied load, the expulsion of water from the voids is highly dependent on the permeability of the medium. The extremely low permeability in the case of clay leads to a slow void contraction. The compression of saturated, low permeability layers under a static pressure is known as consolidation. The consolidation rate depends on the compressibility of the soil (rate of decrease in volume with stress) and soil permeability, which in turn, is dependent on the viscosity of the liquid. An increase in temperature increases the consolidation rate but does not affect total amount of consolidation.

Based on the study, Koçak and Köksal [30] found that among other reasons, the effect of the railway as one of the big contributors to the settlement of the Little Hagia Sophia Mosque (*Church of St. Sergius and Bacchus*) *– Istanbul, Turkey*. They found that the railway, which was operational for 50 years at 5 m away from the mosque, caused bricks to fall from the nearby wall when trains were passing by. The influence of the railway can increase the settlement with weak soil and high water level. Yardım and Mustafaraj [31] also found that settlement is triggered by earthquakes, frequent changes in underground water level caused by the river base change, changes of ground water level due to surrounding drainage system and constant vibrations generated by the adjacent motorway and railway.

Naik et al. [2011] carried out settlement study for a Institutional Building located in South Goa, India, which developed cracks when the construction had reached till the plinth beam level. It was found that some foundations were located above the natural ground at a depth of 2 m in unconsolidated filled up ground of an abandoned laterite stone quarry, where SPT (Standard penetration Test) was found to be less than 12, which resulted for differential settlement. This differential settlement was observed towards the front left corner of the Building which was lying on the filled up ground. The differential settlement led to cracks in the plinth beam and Foundation Concrete.

2.7. Permeability

The amount, distribution, and movement of water in soil have an important role on the properties and behavior of soil. The engineer should know the principles of fluid flow, as groundwater conditions are frequently encountered on construction projects. Water pressure is always measured relative to atmospheric pressure, and water table is the level at which the pressure is atmospheric. Soil mass is divided into two zones with respect to the water table: (i) below the water table (a saturated zone with 100% degree of saturation) and (ii) just above the water table (called the capillary zone with degree of saturation ≤ 100%) [14].

Data from field permeability tests are needed in the design of various civil engineering works, such as cut-off wall design of earth dams, to ascertain the pumping capacity for dewatering excavations and to obtain aquifer constants [14]. The permeability of soils has a decisive effect on the stability of foundations, seepage loss through embankments of reservoirs, drainage of subgrades, excavation of open cuts in water bearing sand, and rate of flow of water into wells [10].

Prakash and Jain [16] explained that water flowing through soil exerts considerable seepage forces, which have direct effect on the safety of hydraulic structures. The rate of settlement of compressible clay layer under load depends on its permeability. The quantity of stored water escaping through and beneath an earthen dam depends on the permeability of the embankment and the foundation respectively. The rate of drainage of water through wells and excavated foundation pits depends on the coefficient of permeability of the soils. Shear strength of soils also depends indirectly on its permeability, because dissipation of pore pressure is controlled by its permeability. According to U. S. Bureau of Reclamation, soils are classified as (i) Impervious: k (coefficient of permeability) less than 10^{-6} cm/sec, (ii) Semi pervious: k between 10^{-6} to 10^{-4} cm/sec (iii) Pervious: k greater than 10^{-4} cm/sec.

The Hsinchu is located from north to south along the west coastal plain of Taiwan. Taiwan is a seismically active region and has governing seismic design criteria similar to those used in the International Building Code (IBC). At the foundation construction site, different layers were found at different depth like fill (soft, silty clay with variable amounts of sand, gravel, and organic material) clay (medium stiff to stiff, silty clay) Gravel/Cobble. The hydraulic conductivity (permeability) varied accordingly. The use of permanent drainage systems under the floor slab to draw down the groundwater table allowed the buildings to be supported on the more cost effective shallow footings and slab-on-grade floors [44].

2.8. Shear Strength

The shear resistance of soil is the result of friction and the interlocking of particles and possibly cementation or bonding at the particle contacts. The shear strength parameters of soils are defined as cohesion and the friction angle. The shear strength of soil depends on the effective stress, drainage conditions, density of the particles, rate of strain, and direction of the strain. Thus, the shearing strength is affected by the consistency of the materials, mineralogy, grain size distribution, shape of the particles, initial void ratio and features such as layers, joints, fissures and cementation [32]. The shear strength parameters of a granular soil are directly correlated to the maximum particle size, the coefficient of uniformity, the density, the applied normal stress, and the gravel and fines content of the sample. It can be said that the shear strength parameters are a result of the frictional forces of the particles, as they slide and interlock during shearing [33]. Soil containing particles with high angularity tend to resist displacement and hence possess higher shearing strength compared to those with less angular particles [34].

Different researchers [14, 16, 19] explained that the capability of a soil to support a loading from a structure, or to support its overburden, or to sustain a slope in equilibrium is governed by its shear strength. The shear strength of a soil is of prime importance for foundation design, earth and rock fill dam design, highway and airfield design, stability of slopes and cuts, and lateral earth pressure problems. It is highly complex because of various factors involved in it such as the heterogeneous nature of the soil, the water table location, the drainage facility, the type and nature of construction, the stress history, time, chemical action, or environmental conditions.

As per Prakash and Jain [16], confining pressures play the significant role in changing the behavior of soils in deep foundations. Similarly in high rise earth dams, the confining pressures are of very high magnitude. Triaxial test is the only test to simulate these confining pressures. For short term stability of foundations, dams and slopes, shear strength parameters for unconsolidated undrained or consolidated undrained conditions are used, while for long term stability shear parameters corresponding to consolidated drained conditions give more reliable results.

Akayuli et al. [35] found that the friction angle is high for a sandy soil than its cohesion and vice versa for clayey soil. Shanyoug et al. [36] in their study concluded that there is a general increase in cohesion with clay content. As more clay is introduced into the sandy materials, the clay particles fill the void spaces in between the sand particles and begin to induce the sand with interlocking behavior. Hence, clayey sand soils are expected to exhibit low cohesion whereas the cohesion increases with high clay content.

Dafalla [27] observed that the mineralogy can have a major role in the shearing strength capacity of clays. The cementation between particles can either be due to a chemical bond or physicochemical bond. Swelling and shrinkage in expansive soils are of two extreme opposite effects on the shearing strength. The shear strength is generally low for fully expanded clay while dry shrinking clay is capable of developing higher cohesion and angle of internal friction. The study indicated that choosing the appropriate mix or using appropriate quantity of clay, can help to achieve required shear strength. Very moist clay-sand mixture showed steep drop in both cohesion and angle of internal friction when the clay content is high.

According to Murthy [10] and El-Maksoud [37], cohesion is mainly due to the intermolecular bond between the adsorbed water surrounding each grain, especially in fine-grained soils. As per Mollahasani et al. [38], the soils with high plasticity like clayey soils have higher cohesion and lower angle of shearing resistance. Conversely, as the soil grain size increases like sands, the soil cohesion decreases.

During two case studies of embankment dams in Iran, Karmi et al. [41] found that for large dams, internal friction angle has more critical role in stability analysis than cohesion parameter.

3. Concluding Remarks

Researchers found that different geotechnical properties of soils have different behavior on the structures. Higher the specific gravity, higher will be the load carrying capacity of soils. Density index is used for the compaction of coarse grained soils. Consistency limits indicate the properties of fine grained soils; accordingly fine grained soils can be used for the construction of low permeable layer for disposal of solid wastes and core in earth dams. Particle size shows the gradation of soils, which helps in construction of roads, dams, embankments, design of filters, etc. Compaction improves the bearing capacity of soils. Consolidation properties of soils indicate the settlement of structures. Permeability gives the idea about the stability of foundations, seepage through embankments, etc. Shear strength is the most important geotechnical property of soils, help in stability of civil engineering structures on or below the earth. The interactions among different geotechnical properties of soils can help the researchers while designing the foundations for different types of civil engineering structures.

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