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Ground Versus Soil: A New Paradigm in Geotechnical Engineering Education

M.R. Madhav
Professor Emeritus, JNTU & Visiting Professor, IIT, Hyderabad, India, madhavmr@gmail.com

S.V. Abhishek
Research Scholar, Purdue University, West Lafayette, USA, svabhi.92@gmail.com

SUMMARY: Some of the practitioners of geotechnical engineering tend to confuse Ground with Soil. It is not just semantics but the terms have deeper technical and philosophical implications. Soil is a material which can be handled, felt, seen, smelt, tasted, and tested in small to medium size samples while 'Ground' is an entity that exists in-situ. Just as the adage, 'The total is more than the sum of the individual parts', predicting the behavior of ground from the so-called properties measured on samples collected from the field is much more complex and involves judgment. Ground is an intricate natural entity very similar to 'Humans' and exhibits behavioral responses rather than merely possess properties like other engineering materials. Humans have organs and traits such as being jovial, sad, friendly, angry, misanthropic, etc. but do not have properties. Their behavioral responses depend on genetics, environment in which they grow, personality they develop and to impetus they experience. Similarly, the genetics of ground is defined by its formation (alluvial, marine, residual, colluvial, aeolin, etc.) depending upon how physiogamy forms the deposit. Ground, one tends to believe, is a solid mass on which structures are built, becomes suddenly a fluid under specific aggravating circumstances such as consisting loose saturated sand with small amount of fines but subjected to seismic activity of medium to high intensity. On the other hand, a river in flood can erode the ground by removing particles by its high velocity leading to scour. Slopes on which civilizations thrive, become unstable and sometimes even catastrophic under heavy rainfall, coupled with human activities of deforestation, cutting/steepening of slopes, saturating it by ignorance or callousness, etc. The paper presents a new paradigm that emphasizes the need to visualize Ground, not just as a material but rather an entity, and view Geotechnical Engineering comprehensively, beyond a mechanistic standpoint.

KEYWORDS: Ground, entity, human, medicine, diagnosis

1 INTRODUCTION

Engineers normally deal with materials such as steel, cement, concrete, aluminum, fibers of glass or carbon, liquids such as water or oil, etc. Materials are defined as those made of matter, are non-spiritual, and possess constant well-defined properties such as density, elastic modulus, compressive and tensile strengths, flexural stiffness etc. These are unique to each material and are the same no matter who conducts and where the tests are conducted. Hence, they can be listed in codes/tables and are readily accessible. On the other hand, an 'entity' or 'being' is an object that has life and thus reacts to stimuli.

Since Soil Mechanics, a precursor to Geotechnical Engineering, has come into being in the early 1920s, soil is being treated as a material in the same molds as all other man-made engineering materials. This distinction between natural and manufactured materials is often obfuscated and as a result the practice of Geotechnical Engineering is carried out on the premise that the properties of soil can be determined uniquely. Occasionally, one does consider soil as a geologic material but accidentally tends to assign unique values to the so-called properties. It is the objective of this paper to suggest a paradigm shift in conventional thinking from a 'material' to an 'entity' centered approach while dealing with soil in general but specifically 'ground'. While the central kernel of the analysis may remain traditional mechanistic, the final judgement or decision should be based on a broader perspective of treating the ground as an entity that has many characteristics fairly similar to a human being. Thus, both the approaches are complimentary and not contradictory.

2 NATURE OF SOIL

Soil is a complex three-phase material formed over a long period of time from physical and chemical weathering of parent rock. Soil can neither be termed as a solid nor as a liquid, the behavior changing with either water content or dynamic input. For instance, the states of fine-grained soils are known to vary from liquid, plastic, semi-solid to solid states, with changes in water content. Loose saturated coarse-grained soils may lose all their strength and get liquefied during a seismic event of sufficient intensity. However, ground improvement techniques such as vibro-compaction and heavy tamping help densify such soils and mitigate liquefaction. Following densification, several granular materials gain strength with time by particle readjustment, cold welding etc., a phenomenon similar to thixotropy of fine-grained soils.

Upward flow of water through a granular medium in particular can lead to the phenomenon of 'quick' condition wherein the ground loses its strength. Furthermore, soils that are relatively stiff and strong may lose their strength and stiffness upon disturbance. In fact, sensitivities of the order of 100 or even more are not uncommon. Thus, soil can be characterized as a porous, saturated/unsaturated, non-homogeneous, anisotropic, inelastic (elasto-viscoplastic), dilatant, sensitive, with failure state varying from brittle to ductile, and a material with memory (preconsolidation stress, overconsolidation ratio).

3 PREDICTABILITY OF RESPONSE

Geotechnical engineers perform basically two types of analysis, one for stability and the other for serviceability. Examples of stability analyses include estimation of bearing capacity of foundations, lateral stresses on retaining structures, and stability of natural or man-made slopes and embankments. A factor of safety usually accounts for most of the uncertainties of soil as a material, the method of analysis, etc. The actual performance of the structure is unknown except to the fact that either it exists or has failed or collapsed, unless it has been instrumented and monitored. Thus, we have several conferences on Case Histories in Geotechnical Engineering, Predictive Behavior symposia, etc.

3.1 Drilled Shaft

Figure 1 compares the measured capacity of an 18 in. (457,2 mm) diameter, 50 ft. (15,2 m) long drilled shaft with predictions made by several geotechnical consultants and practitioners in the academic and non-academic fields. The drilled shaft was constructed through 23 ft. (7 m) of poorly graded sand overlying 45 ft. (13,7 m) of soft to medium clay. Apart from the total capacity, the shaft resistance of the pile in the sand and clay layers, as well as the base resistance, are shown in Figure 1. The measured ultimate capacity of the drilled shaft was 410 kips (1824,5 kN). Contrastingly, the predicted ultimate capacities varied from as low as 130,5 kips (580,8 kN) up to a high value of 518 kips (2305,2 kN). Thus, the predicted values ranged from 0,32 to 1,26 times the measured value, which is a substantial range. Out of twenty predictions, only two (predictions 1 and 2) were close enough while thirteen of them grossly underestimated the pile capacity and one overestimated the capacity.

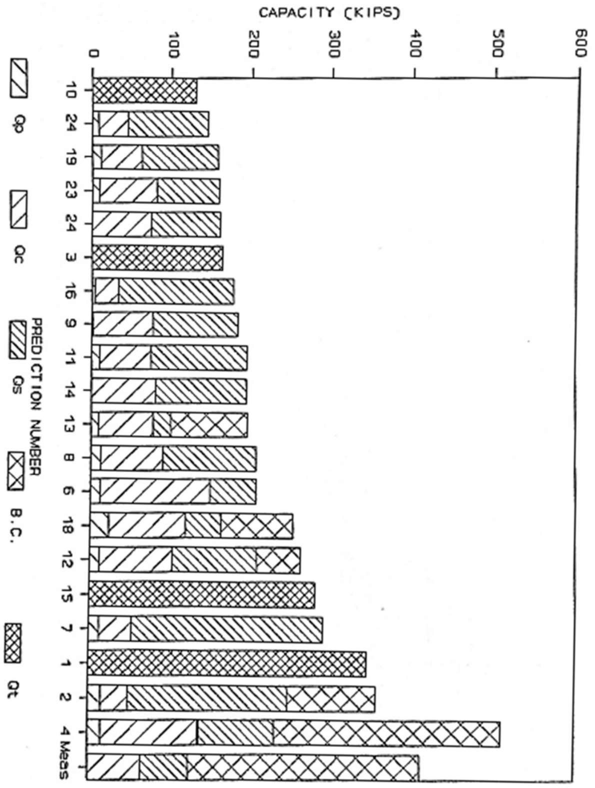

Figure 1. Comparison of predicted and measured drilled shaft capacities (Finno 1989)

3.2 Deep Excavation

Figure 2 depicts the geometry of a 32 m deep excavation in Berlin sand using three rows of prestressed anchors connected to a diaphragm wall. The excavation was conducted in four steps after lowering the groundwater table. The anchors were 20–24 m long, spaced at 1,3–2,3 m and inclined at 27^0 to the horizontal. The moist unit weight and angle of shearing resistance of the sand were 19 kN/m^3 and 35^0 respectively. The problem was part of a benchmarking exercise specified by the German Society for Geotechnics and sent to 17 universities and companies all over the world who were known to perform numerical analysis.

Figure 3 shows the predicted horizontal displacement profiles of the wall by the 17 groups. The horizontal displacement of the top of the wall varied between -229 mm and +33 mm (-ve for displacement towards the excavation). It can be observed that the differences in the horizontal displacements and deflected shapes of the wall, predicted by several predictors, are quite remarkable.

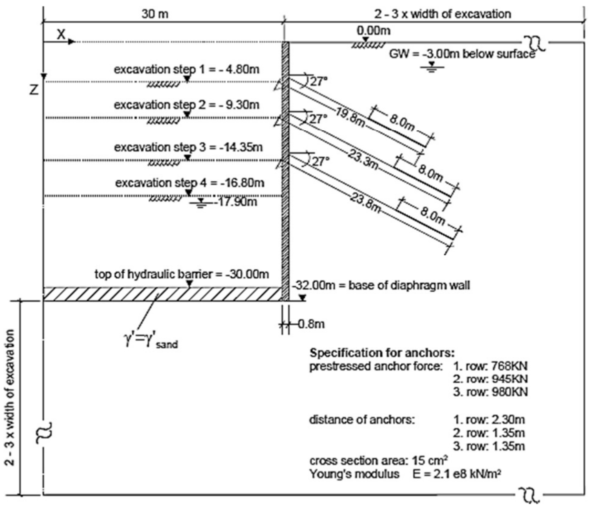

Figure 2. Geometry of deep excavation in Berlin sand (Schweiger 2002)

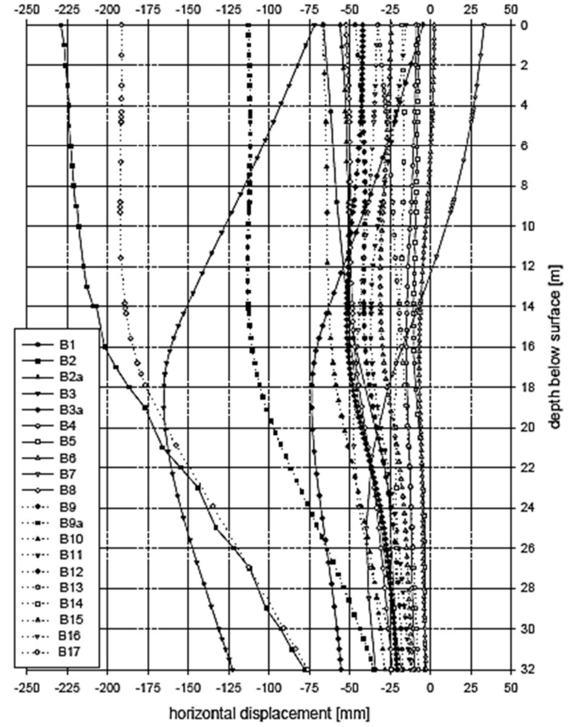

Figure 3. Wall deflection at final excavation stage (Schweiger 2002)

Figure 4 presents the predicted surface settlement profiles of the ground behind the wall. The settlement predictions varied from -275 mm to +40 mm (+ve for heaving of ground). A hypoplastic model without consideration of intergranular strains was used by group B3 to predict the -275 mm settlement, whereas, the +40 mm surface heave was predicted by group B7 using an elastic–perfectly plastic constitutive model with constant ground stiffness. The variation in the pullout forces predicted in the three rows of anchors is also enormous (Figure 5). Schweiger (2002) reported significant differences in the results obtained even in cases where the same software was employed by different users.

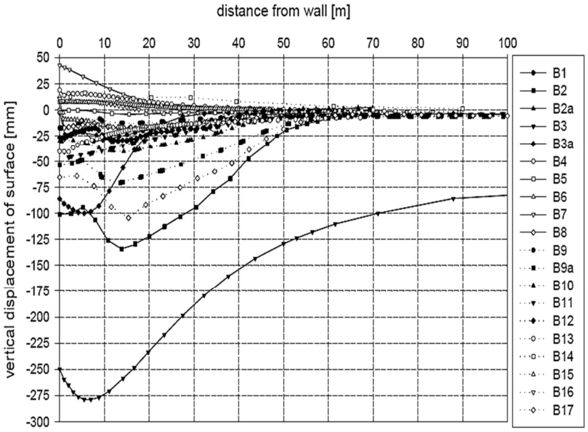

Figure 4. Settlement profiles of ground surface at final excavation stage (Schweiger 2002)

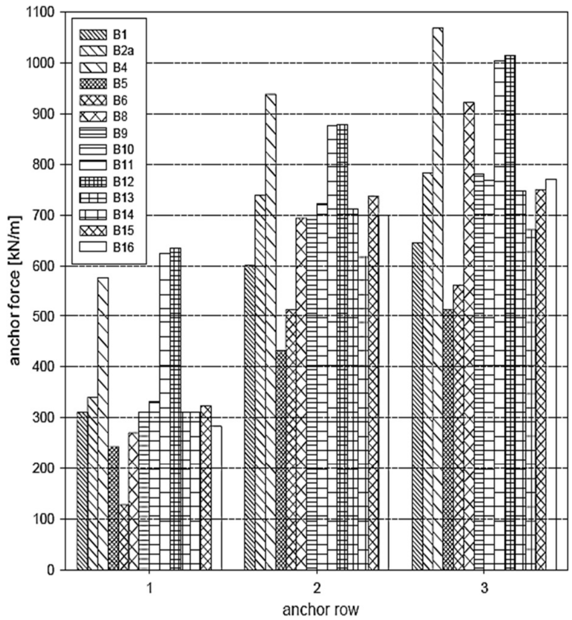

Figure 5. Anchor forces at final excavation stage (Schweiger 2002)

Figures 1 through 5 thus bring out an important result; either our ability to predict the response of the ground to imposed loads using mechanistic approach is inadequate or that the ground does not fit into the conventional concept of a 'material' and hence its response is to be predicted conjointly with non-mechanistic view as well. Predicting the behavior of the ground requires proper judgement and knowledge of several factors such as its origin, past history, environment in which it exists/operates, etc.

4 NON-UNIQUENESS OF GRAIN SIZE DISTRIBUTION AND ATTERBERG LIMITS

The grain size distribution (GSD) and Atterberg limits are probably the most basic and fundamental 'properties' of soil. Table 1 illustrates the sensitivity of these properties to the process of determining the same. The Atterberg limits and GSD were determined for natural and washed soils in moist, air dried and oven dried conditions. The response as measured can vary significantly. The liquid limit of natural soil reduced from 108,0% to 73,0% and 56,5% for air and oven dried conditions, respectively. The plastic limit also reduced in the same form but not as dramatically; however, the plasticity index got affected because of the sensitivity of the liquid limit. A similar response can be observed for soil that has been washed prior to testing.

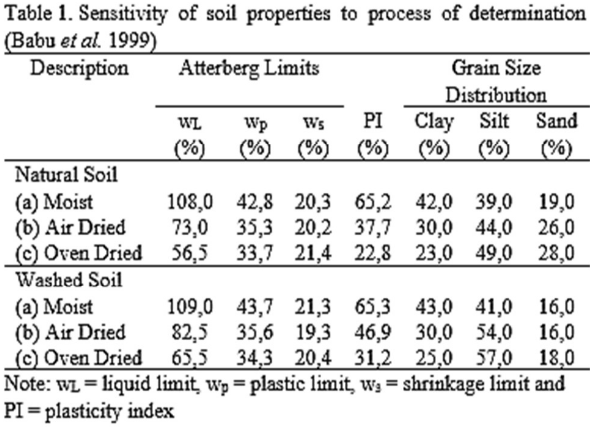

Table 1. Sensitivity of soil properties to process of determination (Babu *et al.* 1999)

Description	Atterberg Limits				Grain Size Distribution		
	w_L (%)	w_P (%)	w_S (%)	PI (%)	Clay (%)	Silt (%)	Sand (%)
Natural Soil							
(a) Moist	108,0	42,8	20,3	65,2	42,0	39,0	19,0
(b) Air Dried	73,0	35,3	20,2	37,7	30,0	44,0	26,0
(c) Oven Dried	56,5	33,7	21,4	22,8	23,0	49,0	28,0
Washed Soil							
(a) Moist	109,0	43,7	21,3	65,3	43,0	41,0	16,0
(b) Air Dried	82,5	35,6	19,3	46,9	30,0	54,0	16,0
(c) Oven Dried	65,5	34,3	20,4	31,2	25,0	57,0	18,0

Note: w_L = liquid limit, w_P = plastic limit, w_S = shrinkage limit and PI = plasticity index

The plasticity index reduced from 65,2% to 37,7% and 22,8% for natural soil and from 65,3% to 46,9% and 31,2% for washed soil under moist, air and oven dried conditions, respectively. While the shrinkage limit was least affected by these conditions and processes, the grain size distribution (clay, silt and sand contents) was affected to different degrees.

5 SHEAR TYPES AND TESTS

Analysis of stability is one of the most common tasks a geotechnical engineer carries out. Figure 6 depicts an embankment constructed on soft ground. A typical failure surface is usually assumed and the factor of safety is computed for this configuration. The question is what value of undrained strength should be assigned to the ground which is in saturated condition? The state of soil along the assumed failure surface varies from an ‘active’ state beneath the embankment to ‘simple or pure shear’ at the deepest point and to a ‘passive state’ at the farthest end. Is the undrained shear strength of ground a ‘unique’ property or does it depend on the manner in which it is determined? The undrained shear strength of a sample of soil from the ground can be determined in direct shear (DS), direct simple shear (DSS), plane strain compression (PSC), plane strain extension (PSE), triaxial compression (TC) and triaxial extension (TE). The direction of principal stresses and the manner in which they are applied is different for each test (Figure 7).

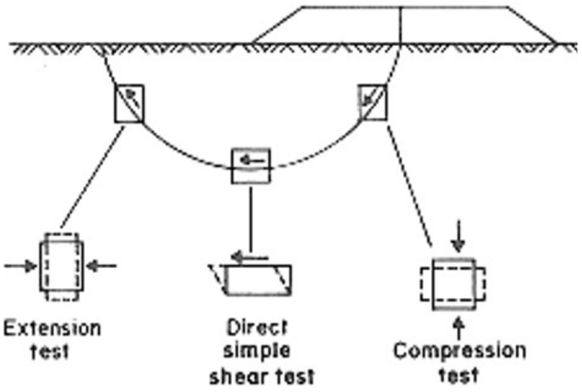

Figure 6. Types of shear along failure surface of embankment on soft ground

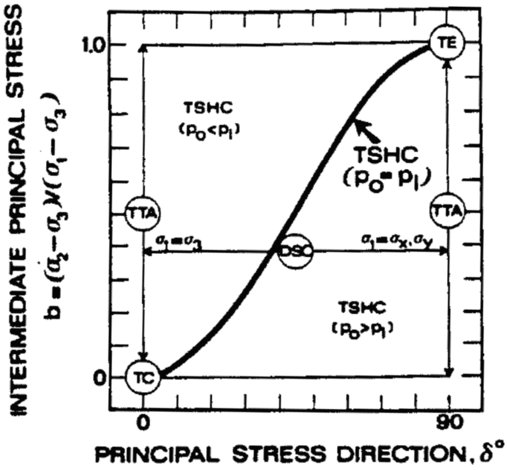

Figure 7. Stress states for different shear tests (Jamiolkowski *et al.* 1985)

The parameters of importance are the direction, δ, of principal stress, the relative magnitude of intermediate principal stress, $b = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ and their variations during the test. The major principal stress is oriented in the vertical direction and b = 0 for TC while the major principal stress rotates by 90^0 and b = 1 for TE. The value of b is intermediate to 0 and 1 and close to about 0,4 for PSC and PSE. The orientation of the major principal stress is somewhat indeterminate and variable for DS and DSS tests.

Figure 8 illustrates the variation of the undrained strength ratio, s_u/σ'_{vc}, with the overconsolidation ratio (OCR) of New Jersey marine clay for K_0-consolidated undrained (CK_0U) TC, TE, PSC, PSE and DSS tests. S and m are the parameters of the Stress History and Normalized Soil Engineering Properties (SHANSEP) technique (Ladd and Foott 1974). The undrained strength ratio for TC increases from 0,32 to 1,6 for OCR increasing from 1 (normally consolidated) to 7.5 (highly overconsolidated). The corresponding increases for DSS and TE tests are 0,27 to 1,25 and 0,2 to 1,13 respectively. The undrained strength ratio for PSC and PSE increases from 0,36 to 0,84 and 0,22 to 0,64, respectively, for OCR increasing from 1 to 3. Thus, soil at a given OCR exhibits different strengths from different shear tests and does not have a unique undrained shear strength.

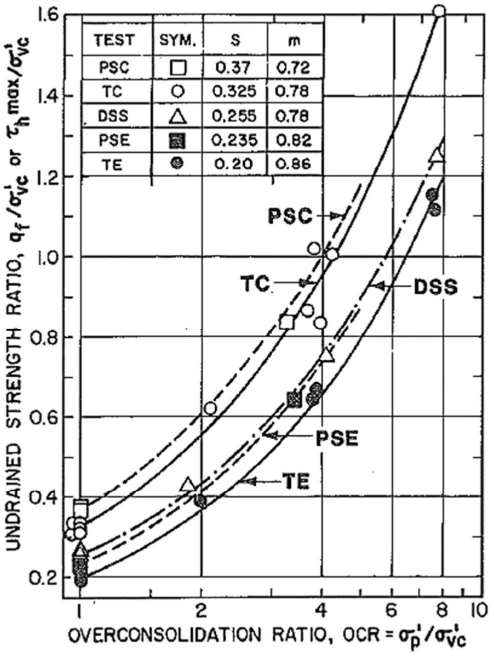

Figure 8. Normalized undrained strength versus OCR from CK_0U tests (Koutsoftas and Ladd 1985)

6 PRACTICES OF MEDICINE AND GEOTECHNICAL ENGINEERING

Several similarities can be drawn or observed between the practices of medicine that deals with the human body and geotechnical engineering that deals with the ground. Firstly, both are not manufactured to specifications, though of late, cloning is becoming possible. Secondly, both the human body and the ground have evolved over long periods of time, by natural evolution in the case of the former, and by geological processes in the case of the latter. Table 2 compares and contrasts a human being with ground. A human being has the usual set of organs, limbs, bones, muscles etc. While these features appear to be the same for most human beings, however, each human is very different from another because of genetics, pedigree, upbringing, parental care, environment etc. Thus, we have extroverts or introverts, traits such as sad/happy, helpful (friendly), neutral or unfriendly, positive or negative attitudes, etc. When it comes to medical attention, humans consult a doctor either for a general checkup, to get treated when ill or sick, to get vaccinated as a preventive measure against diseases, etc.

Table 2. Comparison of human body and ground

Human Body	Ground
Eyes, Nose, Ears, Organs, Bones, Muscles	Different Strata, Soils – Properties/Characteristics
+	+
Genetics/DNA	Formation, Geology
Environment	In-Situ Conditions
Personal History	Past History of Site
Mood Changes	Water Table Fluctuations
Evolution with Age	Thixotropy
Stimuli	Stress/Strain Path
=	=
Behavioral Response	Behavioral Response

Additionally, sports medicine has come into vogue to help athletes recover from injuries (if used properly), and when misused, enhance performance through banned drugs leading to doping.

6.1 Diagnosis and Treatment

A doctor while dealing with a patient goes through two major steps, namely, diagnosis and treatment. The treatment may consist of prophylactic or therapeutic measures. Table 3 presents diagnostic parallels between medicine and geotechnical engineering. In the case of medicine, the diagnosis typically starts off with a qualitative and simple examination of the physical features such as eyes, tongue, skin, etc. of the patient.

Table 3. Diagnostic parallels

Item	Medicine	Geotechnical Engineering
Background	Patient's History, Family Background, Environment	Site History, Geology, Adjacent Structures
Qualitative Examination	Visual, Eyes, Tongue, Skin, Chest, etc.	Reconnaissance, Surface Features, Water Table
Quantitative Tests	Height, Weight	Atterberg Limits, GSD, Clay Content, Mineral Type, etc.
State Parameters	Temperature, Pulse	Relative Density, Liquidity Index
Routine Tests	Pathological, X-ray, etc.	Permeability, Consolidation, Shear Tests; In-Situ Tests such as SPT, CPT, Vane Shear
Specialized Tests	Ultrasound, CAT Scan, MRI etc.	Piezocone, Pressuremeter, Dilatometer, SASW

The doctor may enquire about the patient's family background, environment, history of previous illnesses, etc., and then perform some index type tests such as height, weight, blood pressure, pulse of patient and so on. Conventional pathological or radiological (X-ray) tests may be suggested if warranted. Modern day medical practice is relying more on advanced investigations such as ultrasound, computerized axial tomography (CAT) scan, magnetic resonance imaging (MRI), which are non-invasive but provide a very detailed and reliable picture of a patient's inner vitals.

On the other hand, a geotechnical engineer given a job first undertakes a reconnaissance survey of the site and tries to gather information related to the history of the site and adjacent structures. The geotechnical engineer would then collect few soil samples either by hand augering or by making a trial pit, and may run index tests such as grain size distribution, Atterberg limits, etc., for identification and classification of soil type. As part of the detailed investigations, the so-called 'undisturbed' samples are collected, taken to the laboratory and tested for strength, compressibility, hydraulic conductivity and stress–strain response. Since obtaining truly undisturbed samples is near impossible, in-situ tests such as standard penetration test (SPT), cone penetration test (CPT) and vane shear test are conducted to evaluate the in-situ characteristics of the ground. With modern day advances, the pressuremeter, the dilatometer or spectral analysis of surface waves (SASW) tests may be carried out to obtain more reliable characteristics of the ground.

6.2 Problems

Several similarities exist between the problems faced by doctors and geotechnical engineers (Table 4). Genetically, some people have a tendency to be obese while some others develop anorexia, a problem similar to expansive soils and soil shrinkage. Giddiness is somewhat similar to instability, epilepsy to liquefaction, fatigue to strain softening under cyclic loading, high blood pressure to high pore water pressure, prostrate and urinary problems to drainage, cancer to contaminated ground and groundwater.

Table 4. Problems in medical and geotechnical practices

Medical Problem	Geotechnical Problem
Obesity/Anorexia	Swelling/Shrinkage
High Blood Pressure	High Pore Pressure
Fatigue	Degradation under Cyclic Loading
Giddiness	Instability
Epilepsy	Liquefaction
Fracture	Brittle Failure of Stiff Soils/Rocks
Prostrate/Urinary	Drainage
Cancer/AIDS	Contaminated Ground

6.3 Solutions/Comparative Practices

It is therefore not difficult to draw parallels in dealing with many of the ailments of diseases and the solutions practiced by geotechnical engineers (Table 5). Bypass surgery or insertion of stents into the arteries of the heart allows increased blood flow from the heart to the other parts of the body. Similarly, vertical drains are provided to accelerate consolidation and increase the flow of water through fine-grained soils. Physiotherapy is a physical medicine and rehabilitation specialty that remediates impairments and promotes mobility through fitness and weight training programs. It is somewhat akin to heavy tamping which involves dropping a heavy weight from a large height on top of loose granular soils to improve their relative density. Surgical removal is analogous to soil extraction, a technique used to stabilize The Leaning Tower of Pisa.

Table 5. Similarities in practices

Medical Practice	Geotechnical Practice
Bypass Surgery	Vertical Drains
Vaccination	Preloading
Physiotherapy	Heavy Tamping
Transplants	Inclusions, e.g. Granular Piles/Stone Columns
Dialysis	Electro-Osmosis
Transfusion	Grouting
Orthopedics	Nailing
Chemotherapy	Remediation of Contaminated Ground
Surgical Removal	Excavation/Soil Extraction

Organ transplantation involves moving of an organ from one body to another to replace the recipient's damaged or absent organ. Granular piles/stone columns perform a similar function by replacing soft/weak ground with granular material having higher shear resistance. Orthopedics deals with the strengthening of deformities or functional impairments of the musculoskeletal system, which is akin to soil reinforcement by nailing or geosynthetics. Vaccination uses a mild dose of antigenic to increase body resistance, while soft ground is preloaded to withstand regular load after the removal of surcharge. Chemotherapy, which is used to treat cancer, is comparable to remediation of contaminated ground.

6.4 Major Differences

While there are several parallels between the practices of medicine and geotechnical engineering, there are, however, some major differences:

1. In medicine, the patient goes to a doctor while a geotechnical engineer has to go to the site to diagnose the problem.
2. The patient talks to the doctor whereas a geotechnical engineer listens to the ground.
3. The failures of doctors are often buried or cremated in the ground, whereas the successes of geotechnical engineers get buried and failures show up glaringly.
4. Doctors are paid much more handsomely than geotechnical engineers.
5. Lastly, just as in the practice of medicine where quacks pose as qualified doctors and harm the society, several fly-by-night kind of geotechnical agencies exist that first underquote and then put in fictitious values in their report. Therefore, a good quality geotechnical investigation should always be encouraged even if it costs a little more because rectification in the event of a failure increases the overall cost and time of the project by several folds. Prevention any day is better than cure.

7 CONCLUDING REMARKS

The purely mechanistic view that postulates that materials have unique and determinable properties does not adequately describe the response of soils in general and ground in particular. The gross unpredictability of the behavior of a drilled shaft and a deep excavation attest to the aforesaid fact. Instead, ground exhibits behavioral responses somewhat akin to entities like living organisms that respond to stimuli. A parallel has been drawn between the fields of medicine and geotechnical engineering, and similarities and contrasts between the two have been presented. It is illustrated that soil as a material and ground in particular should be examined, evaluated and understood from a framework similar to that used for examining human beings. Thus, a paradigm shift is needed in geotechnical engineering education to visualize ground as an entity, recognize the non-uniqueness of several of its properties and apply proper judgement for selection of appropriate parameters to be used in the analysis/design of the problem at hand.

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