

SOIL MECHANICS PRINCIPLES IN CONSTRUCTION PRACTICE

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Abstract : The application of Soil Mechanics principles in day to day construction practice involves an appreciation and keen understanding of soil properties and soil behavior in order to provide adequate and cost effective solutions. Oftentimes, the fundamental understanding of soil behavior and how to apply it to advantage is lost leading to costly mistakes and time delays. This paper aims to unify Soil Mechanics principles and Fundamental knowledge to the solution of construction problems involving earthworks and foundation.

Further reading is recommended as this paper in no way can claim to be complete in defining soil behavior and the various factors influencing its properties and behavior.

Key words: *Soil behavior, soil mechanics, Liquefaction, particulate behavior, highly fractured rocks, swelling soils, shear strength, phi Ø Angle.*

1 INTRODUCTION

The Construction professional is oftentimes confronted by seemingly puzzling problems in construction defying solutions. These problems particularly occur during earthworks or foundation construction. Unlike the construction of the superstructure where the professional is familiar with the properties and behavior of man-made construction materials, working with the soil is often times fraught with uncertainties and sometimes with the unknown behavior of soils and rocks.

These uncertainties happen due to various factors that are not known immediately because soil is a *natural material* and has varying characteristic properties and behavior depending on a myriad of factors which need to be understood.

The following are some of the factors that have a likely effect on the final soil behavior or characteristic property:

- *Soil or Rock Mineralogy*
- *Manner of Physical Deposition*
- *Presence or absence of Water*
- *Effect of Physical forces acting on it such as load history or Disturbances from Vibration etc.*

We shall also discuss the Problems and solutions that are influenced by the foregoing factors and some, by citing various experiences encountered in normal day to day

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construction activities.

2 SOIL OR ROCK MINERALOGY

2.1 Soil as a Particulate Material

Under a very powerful electron Microscope, even a piece of seemingly solid mass of clay appears as an assemblage of particles with some orientation. This orientation surprisingly can be altered by reworking of the clay, addition of or removal of moisture or by altering the chemical make-up of the porewater.

Under normal conditions, it would also be noted that the assemblage includes water and air. The water is either captured or *adsorbed* water or free water.

The process of compaction is nothing but the expulsion of air (*reduction of voids in the soil*). Thus, our attention is directed as to how this could be most efficiently done.

However, as we know, this assemblage that we just saw in the Electron Microscope is only but one of two major assemblages that soil can assume depending on its granulometry or Grain Size.

Soil can either be:

- **Coarse Grained (*Sand*) or Cohesionless**
- **Fine Grained (*clay*) or Cohesive**

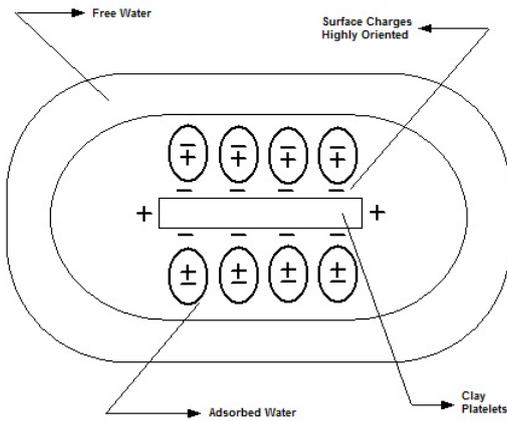
The clear distinction between the two are somewhat obscured by their combinations or mixtures that could be found in nature. In their unadulterated states, the differences become readily apparent or clearly distinguishable.

2.2 Clay Microstructure

Let us now peer again at our microscope to look at a sample

of cohesive or fine grained clay soil.

The Individual Clay Platelet



As we can see, the clay is composed of submicroscopic platelets surrounded by Electrical charges, a closely held layer of adsorbed water and an outer layer of loosely held water. The interparticle distances, measured in *Angstroms* Å are governed not only by the particle orientation but also by the Electrical forces of attraction as well as the thickness of the adsorbed and free water. It would take a very high input of energy in order to dislodge or remove the adsorbed layer. However, the loosely held water can be removed in the field by sample air drying or windrowing or application of pressure. Once the free water is removed, compaction can be attained. These electrochemical forces give the clay its characteristic strength known as *Cohesion*. The particle orientation as we shall see in the succeeding table also affects some other physical performance characteristics of the soil.

2.3 Microstructure of Fine Grained Soils

Fine Grained Soils, because of their sub microscopic size are influenced by Electrical and Chemical forces of attraction and repulsion. This is due to the fact that the ratio of specific surface area to their volume is so large that surface electrical activity greatly influences the behavior of fine grained soils.

In nature, fine grained soils assume a *flocculated* or *dispersed* configuration as shown below depending on the manner of deposition and environmental influences that it has been subjected to.

FLOCCULATED



DISPERSED



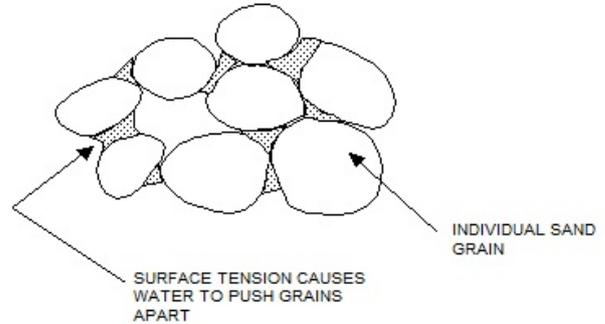
A *flocculated* structure assumes a random tip to side orientation much like a "house of cards" whereas a dispersed structure has the platelets more or less aligned to

each other.

The arrangement of these platelets alone has an influence on the performance and behavior characteristics of the soil.

2.4 Sand Particles

Obviously we do not need a microscope to be able to see the coarser granular structure of sandy soils. In fact this can be done with the naked eye.



Very dry sand in the hand cannot be squeezed into shape whereas semi moist sand when squeezed could hold some shape until it dries out and crumbles. Surprisingly, addition of more water to saturate the sand collapses the sand as in the very dry state. Sand lacks real *Cohesion* and is therefore termed *Cohesionless* soils. It derives its strength in nature through interparticle friction and grain to grain contact stresses. Sands are therefore friction type materials with a *Phi Angle* ϕ to define its characteristic resistance to shearing or sliding. However, this property is not a unique value and would depend on the state of the grain to grain contact arrangement as well as the normal forces that are providing the stress and confinement.

Sand when unconfined and loosely dumped assumes an angle of repose which would correspond to approximately its lowest *Phi Angle* ϕ value.

2.5 Behavior of Highly Fractured and/or Jointed Rocks

A special case of a particulate behavior is highly fractured rock. Although it may appear intact and solid when exposed, highly fractured rock can behave as a *particulate material* when disturbed. Therefore, care in understanding the actual condition of rock is important particularly when making large open cuts in it.

Other than the jointing of the rocks, the dip or inclination of the bedding plane could also sometimes trigger instability in rocks when exposed in cuts simply due to the forces of gravity acting on the *Particulate* rock mass. Thus, care is necessary in trying to predict the actual behavior of rocks whether it will behave as a solid mass or as a *particulate material*. Otherwise, disasters can happen such as in the *Cherry Hills Landslide*.

3 MANNER OF PHYSICAL DEPOSITION IN NATURE OR PLACEMENT IN FILLS

The manner of deposition also influences the physical

behavior of soils particularly for sands but also for clays. Whether laid gently or violently by agents of deposition such as water or wind, the soil behaves in accordance with the final state when deposited.

3.1 Effect of Natural Agents of Deposition

3.1.1 Deposition of Sand in Nature (Water Laid)

When grains of dry sand are gently deposited in a container, they fall into place in a precarious grain to grain contact. A jarring motion imparted on the container causes the grains of sand to assume a denser packing. Slight addition of water causes the sand to swell or increase in bulk while saturation with just enough water that is somehow allowed to drain causes the sand to be compacted into a dense state. This has been known to us since time immemorial as *Hydrocompaction*. This knowledge of *Hydrocompaction* is used for the compaction of clean sands in construction and we shall see why this is so. Perhaps only the mechanism behind it is not well understood.

3.2 Effect of Compactive Effort

Having recognized the behavioral characteristics of soils (*Particulate Material*) we now look at the means to achieve compaction in the Field.

However, try to remember the fundamental response of the two general types of soils to compactive effort.

Loose Clean Granular Soils, because of their precarious grain to grain contacts, are best compacted by causing a jarring motion or vibration such as what a vibratory roller would impart. In addition, saturating the sands *immediately* before compaction allows for increased compaction effectiveness.

Fine Grained Clay Soils; on the other hand respond better to a kneading type of compactive effort such as that imparted by sheepsfoot rollers and pneumatic type rollers as these tend to reorient the platelets. Clays are best compacted by a kneading motion say from a Static sheep's foot or tamper foot roller with a controlled Moisture content very near or at the *Optimum Moisture Content*.

We can therefore see the effective ranges for various compaction equipment under differing soil conditions and we recognize right away that this has something to do with the grain size (*clay to rock*).

At first glance, it could be said that this is a very familiar and well accepted practice.

4 SOIL SHEAR STRENGTH

4.1 Clays

Particulate materials derive their strength from friction or intergranular contact and/or from bonding forces or cohesion as we know it. These bounding forces and friction prevent the particles from sliding.

The most important soil strength property that we have to deal with is the soil's **Shear Strength or Cohesion** since most of the loading that the soil is subjected to causes the individual soil particles to slide or "**shear**" one against the other because of their very fine particulate character.

Depending on the granulometry of the soil and its moisture content, the shear strength is either derived from electrical and chemical forces of attraction (*cohesion*) and repulsion as in clays or by simple *practical* grain to grain contact and friction as in Pure Granular Materials. Since shear strength depends on the integrity of the sliding resistance of the individual soil particles, it only follows that the more compact the soil becomes, the higher the shear strength and vice versa. The only way to cause this increase in strength is to lessen the interparticle distances by the expulsion of air and/or water or by cementing it which is sometimes resorted to as in soil cement if good materials are not readily available.

Near total expulsion of the moisture under high heat will cause the fusion of the clay particles as in pottery.

This leads us to one of the Fundamental Principle in Earth Compaction:

“Increasing Density (Strength) is achieved by decreasing the soil interparticle distance through the expulsion of air or water or both.”

As we shall see later on, reduction of interparticle distances would sometimes require addition of more water into the soil in order to dislodge more water. This statement appears to be confusing and contradicts logic but its proof reiterates the importance of the understanding soil particulate behavior in the solution of Earthwork Problems

Parameter/Property/ Behaviour	Dry of Optimum	Wet of Optimum
Dry Density	same	same
Water Content	low	high
Structure on compaction	flocculated (random)	dispersed (oriented)
Shrinkage on drying	low	high
Swelling on access to water	high	low
Permeability	Isotropic (k)	Anisotropic ($k_v > k > k_h$) ¹²
Compressibility		
at low stress	low	high
at medium stress	high	low
at high stress	same	same
Construction Pore pressures	low	high
Shear behaviour (immediate post-compaction)		
stress-strain	brittle	plastic
peak strength	high	low
ultimate strength	same	same
(after saturation at constant effective stress)		
stress-strain	similar	similar
peak strength	similar	similar
ultimate strength	same	same
c', ϕ'	similar	similar
A-factor at failure	negative	not as negative

¹⁾ k_1 is permeability in a direction parallel to particle orientation.

k_p is permeability in a direction perpendicular to particle orientation

The table above therefore suggests that we can alter the performance and behavior characteristics of the clay soil to suit our specific needs if only we know how.

As an example, an experiment with a clay material was made to determine the effects of compaction water on permeability. It can be noticed that although compaction density is the same left and right of optimum, the permeability values are not the same for this specific type of soil.

4.2 Sands

Sands on the other hand possess frictional resistance which is dependent on the confinement of the soil as well as the normal stresses pressing and the individual grains to have intimate grain to grain contact.

As we have stated, this property, this parameter, known as the Phi Angle ϕ is not unique and depends on the foregoing factors.

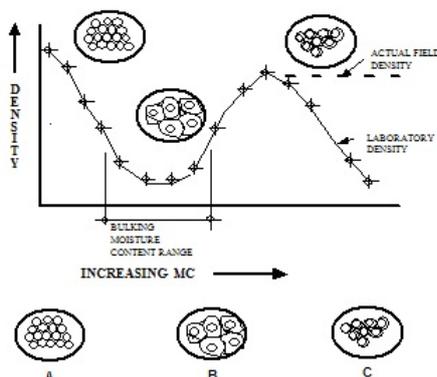
5 PRESENCE OR ABSENCE OF WATER

5.1 Sand

Very dry sand in the hand cannot be squeezed into shape whereas semi moist sand when squeezed could hold some shape until it dries out and crumbles. Surprisingly, addition of more water to saturate the sand collapses the sand as in the very dry state.

When grains of dry sand are gently deposited in a container, they fall into place in a precarious grain to grain contact. A jarring motion imparted on the container causes the grains of sand to assume a denser packing. Slight addition of water causes the sand to swell or increase in bulk while saturation with just enough water that is somehow allowed to drain causes the sand to be compacted into a dense state. This has been known to us since time immemorial as **Hydro compaction**. Perhaps only the mechanism behind it is not well understood.

We now look at the Moisture Density relationship curve for a coarse grained sand with very little or no fines.



Since the individual grains are relatively very large compared to the clay platelets, we know that surface electrical forces play very little influence on the behavior except at a certain moisture content range.

We see right away that the Moisture Density curve indicate two density Peaks “P₁” and “P₂” where density is high. The first Peak P₁ occurs when the soil is very dry (MC = 0) and the other Peak P₂ at almost saturation conditions. We also see that between these two Peaks is a valley where density is lowest.

The reduction in density in this valley as defined by a moisture content range is known as the “**Bulking Range**” for this particular sand.

This reduced density is caused by surface tension forces of the water surrounding the individual grains which tend to drive the adjacent grains farther apart, causing loss of interparticle contact and collapse in the density from the previous high.

However, progressive addition of water beyond the bulking range collapses the surface tension and the additional hammer impacts increases the density again to the second Peak “P₂”. The *laboratory curve* shows a downhill movement in density with increasing moisture content beyond saturation levels.

The real field curve shown by the dotted line suggests otherwise. The reason behind this is that in the laboratory compaction procedure, the water cannot drain within the steel compaction mold and thus the soil becomes a soupy mush. However, in the field, additional water is continually drained and the Peak density is maintained.

This curve clearly shows the **fallacy** of specifying Proctor Compaction Procedures and an **OMC** for clean coarse grained soils, because definitely, the soils are **insensitive to moisture content** except at the very dry and very saturated conditions. Unlike clay soils which follow a typical bell shaped curve, clean coarse grained soils exhibit a typical “S” shaped curve with the Peaks P₁ & P₂ clearly distinguishable.

Peaks P₁ & P₂ may sometimes be equal but this is more of an exception than the rule and their relative maximum values could shift either way depending on the type of soil.

This soil behavior has been recognized by **ASTM** and standardized into two standards **ASTM D-4253** “*Max. Index Density of Soils using a Vibratory Table*” **ASTM D-4254** “*Min. Index Density of Soils and Calculation of Relative Density*” to arrive at a minimum and maximum density. These values are then used to compute the **Relative Density D_R** once the Field Density is obtained.

Compaction is specified not in terms of % of MDD but

rather as **Relative Density D_R** and their relationship to each other is shown in *Scalar Fashion*.

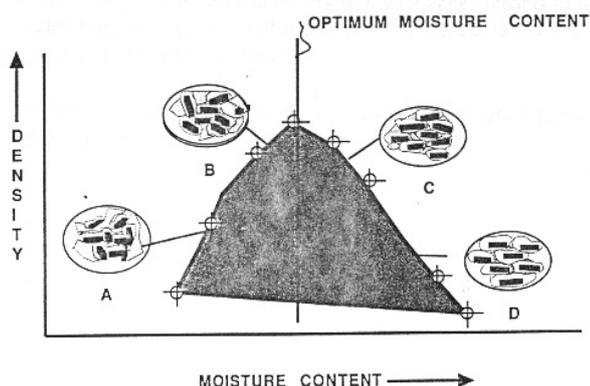
5.2 Clay

In the case of fine grained soils such as clays, interparticle forces play a significant role in the behavior of the soil.

The readily recognized “Bell” shaped curve traces the density of the soil when subjected to increasing moisture content under *laboratory* compaction. The increasing amount of water combined with application of compactive effort increases the density with a change in soil structure. The soil tends to imbibe water until a *Threshold* is reached called the *Optimum Moisture Content (OMC)*. Beyond this, increasing water is absorbed with a corresponding decrease in density as the captured water pushes the individual clay platelets farther and farther apart. The *Laboratory curve* would then assume a perceived *Bell Shape*.

In actuality, and in the field, the increasing moisture content would then to collapse the soil and turn it in to mush or mud.

Thus, beyond the OMC point, any increase in water content would tend to decrease the density and conversely, increasing the compactive effort beyond the optimum will not achieve adequate compaction.



5.3 Swelling Soils

Swelling soils find wide distribution in areas of volcanic deposition or origin with tropical climate and also in arid and/or semi desert climates. In tropical volcanic settings, *Alumina* rich volcanic ash gets deposited in general over a wide area. Some get concentrated in depressions or low areas which are almost always inundated or saturated with water. This regular inundation tends to leach the alumina and concentrate these at the bottom 1.0 meter to 2.0 meters generally but could be deeper depending on the leaching effects.

This explains the sporadic occurrence of expansive soils as generally, the expansive soils are not deposited area wide and thus portions of the project footprint may or may not be underlain by these soils.

In tropical volcanic environments, volcanic soils rich in

alumina are deposited as Aeolian deposits. These Aeolian deposits settle in the land and are thicker in depressed areas. The alumina gets leached and concentrated due to ponding and saturation in the depressed areas. This alumina is the primary source of the expansive tendency and most often are shallow in occurrence due to the limited leveling effects.

Swelling soils are generally fine grained clay soils with very high plasticity. These clay soils have very high affinity for water and the *adsorb* and *absorbed* water tend to push the individual soil platelets apart with relatively very high expansive pressures.

The swelling soil or expansive clay have caused Billions of Dollars of annual Damage in the US and unquantified damage here in our country.

Most often, heave or swell is mistaken as *Settlement* with costly results as the direction of remediation may not be effective at all or even cause more harm as experienced by the author in a specific project.

5.3.1 Moisture Density Relationships

We begin with the all too familiar moisture density relationship known as the “**Laboratory Proctor Test**” for a clay soil.

Our “*total familiarity* with this simple **bell shaped curve** and its universal acceptance as the “*characteristic*” compaction curve has caused most of the problems we encounter today in Earthworks compaction. Too often, it has not been realized that this is not the only shape a laboratory Proctor curve can assume and that grain size and moisture play a great part in influencing the shape of the compaction curve.

This bell shaped curve as, we shall see later on, is only applicable for fine grained soils or soils with significant plasticity as to make it perform as a clay like soil.

As we can see, at the start of the test when the soil is relatively dry, the soil assumes a flocculated structure “**A**” additional mechanical reworking and increasing amounts of water and subsequent expulsion of air and closing of the voids tend to produce a semi flocculated structure “**B**” with increasing density until a peak is attained. This peak is the maximum density that could be attained by that type of soil **in the laboratory**. This is expressed in terms of “*Relative Compaction*” which is a percentage of the maximum dry density obtained in the laboratory test.

The moisture content corresponding to this maximum density is known as the Optimum Moisture Content “**OMC**”. Further compaction and additional water beyond this point result in decrease in density with increasing amounts of water. The soil platelets begin to be oriented and aligned and the interparticle distances tend to widen as more and more water is captured.

Recognition of the two characteristic compaction curves (*The “Bell” and the “S”*) leads us to the realization that clays and sands behave very much differently when compacted and require different approaches and solutions.

We also know now that the behavior of soils can be tempered to suit our requirements as shown in the foregoing table particularly for a clayey soil.

Thus, we are led to the following conclusions:

1. There is not one but two **General** characteristic curves for soils depending on their granulometry.
2. The concept of **Optimum Moisture Content** generally **does not** apply to Clean Granular Soils and therefore the Proctor Standard is inappropriate or could lead to problems in the Field. Clean sands either have to be compacted **very very dry** or **very wet** in order to achieve the maximum density.
3. The microstructure of the soil needs to be considered in the selection of the right compaction equipment.
4. For Fine Grained Soils, although density is the same for corresponding points left and right of the OMC, the performance and behavior of the soil are different due to the alteration in the microstructure arrangement.
5. Beyond the maximum density, additional compaction energy would be detrimental to both clays and sands as breakdown can occur causing a decrease in density.

Therefore, use no more than what is necessary to attain good compaction.

6. For intermediate soils, it would be necessary to determine in the laboratory the characteristic behavior from zero MC to saturation levels.
7. In case the laboratory curve is not clearly defined or when there are doubts as to the behavior in the field, a field compaction trial would be required.

6 EFFECTS OF PHYSICAL FORCES ACTING ON THE SOIL

6.1 Effect of Vibrations on Loose Sands

Loose clean *Dry* sands when subjected to vibrations say from earthquakes, explosives or vibrating machinery tends to rearrange to attain a denser packing by filling up the large void spaces. This rearrangement can cause significantly

large settlements which in turn can cause distress.

This is different from the behavior of Saturated sands when subjected to earthquake or other exciting sources discussed later.

6.2 Soil has an “Autographic Memory”

One very important fact often overlooked is the fact that soil has an *Autographic* memory or it remembers past loading history. If say for example, a soil is loaded in the past by a hill or a mountain or a very old structure, and the load is suddenly removed, the soil remembers the past preload and any load imposed on it not exceeding this past preload will not in any way cause settlement or bearing capacity problems.

This fundamental fact is put to good use when determining the actual *Mobilizeable Soil Bearing Capacity* of buildings on massive cut areas or deep basement levels. The weight of the soil removed is considered as *Overburden Relief* which can be added to the theoretical mobilizeable bearing capacity.

Also, when soft soils are consolidated and stabilized by a load surcharge, the soil remembers this surcharge load and a load slightly less than this surcharge can be imposed on the soil without any further settlement or bearing capacity failure.

7 BEHAVIOR UNDER COMPACTION-CASE STUDIES

Very often the Earthworks Contractor is confronted with a clear set of specifications from the Design Engineer outlining specified compaction density, moisture content and governing standards. In most instances, the contractor innocently and faithfully tries to carry out the procedure in the field without a clear understanding of what is really required and without a fundamental understanding of the Soil Mechanics principles entailed in such a “**simple**” task as Earthwork construction. This ignorance and oversimplification often produces disastrous results, delays in the project and financial loss to the contractor. Unfortunately, it is sometimes not only the contractor but also the Design Engineer who is ignorant of these principles, thus confounding the problem which could again further cause delays in the project. What is also disheartening is the realization that all too often this “**failure**” on the part of the contractor results in countless litigation or delays because the real problem could not be identified.

The statement “**problem identification is Eighty Percent of the solution**” is nowhere very applicable as in this problem.

Let us consider several cases which highlight what we mean:

7.1 Runway Construction Project

A very large runway project inside a U.S. Base required a minimum of 95% of Maximum Dry Density based on ASTM D-1557 (Modified Proctor) on the subgrade which

consisted of Clean Coarse Grained Materials (Granular Sand).

The contractor proceeded to do the compaction utilizing about 20 units of large Vibratory Rollers and Two (2) Water Trucks.

We were hired as the Independent Q.C. Laboratory to monitor Field Compaction. The contractor almost consistently had very large number of Field Density Test **“Failures”** despite numerous passes (about 10 to 12) per lane.

We were asked to look into the problem as substantial delays have been incurred without significant progress. After conducting compaction trials on a 100 meter strip for half a day, we were able to achieve adequate compaction in just 3 passes!

The procedure we used in the compaction trials was immediately implemented which resulted in almost **halving** the vibratory compactor fleet (rented) but increased the number of water trucks to 4 at tremendous savings to the prime contractor. This also enabled the contractor to accelerate subgrade preparation by at least two (2) months.

What happened was not black magic but just the sound application of Soil Mechanics principles as we shall see later on.

7.2 Housing Project at Subic

In a housing project inside the Subic Naval Base, an American Contractor was required by the contract specifications to compact the soil to 95% of Maximum Dry Density again based on ASTM D-1557. After several rectangular slabs for the duplex housing were poured, and after a heavy downpour, two of the recently poured slabs broke neatly into two at the center.

We were called in to do consulting work to solve the problem and we found out that it was a swelling soil problem.

After the study and a long protracted fight with the U.S. Navy Engineers out of Honolulu, the Navy adopted our recommendation on the basis of a **“no-cost change order.”**

Surprisingly, what we recommended was to bring down the compaction levels to 90% of Maximum Dry Density Based on ASTM D-698 instead of the more stringent ASTM D-1557 (Modified Proctor) (The latter having the effect of increasing the energy input or compactive effort by 4.58 times!) and to compact the soil Wet of Optimum.

Clearly this was an **“Inferior”** substitute that was accepted without a reduction in the contract amount.

Why was the change possible?

7.3 Lahar Project

We were again involved to do preliminary consulting work involving **Lahar** as a Construction Material for a significant Lahar Protection Structure.

The initial specifications called for Proctor Densities and Specified the **Optimum Moisture Content required**.

Since the structure would be constructed during the dry season, water was a big problem that could hamper the construction of the structure in time for the next onslaught of Lahar.

We have done preliminary work on Lahar on our own as a matter of professional interest and we knew that Lahar behaved as a clean granular soil.

Therefore, we recommended that the Lahar ought to be even compacted in a very dry state. After a lengthy explanation and initial disbelief, everybody agreed to do so and thus eliminated an unnecessary requirement which could have even hindered the construction progress or even resulted in the specifications not being attainable in the field.

Again, a timely intervention applying sound Soil Mechanics principles saved the day for the project.

7.4 Stalled Vehicle Wheel in Loose Sand

A hypothetical but common case which involves a car wheel stuck in a rut on loose beach sand.

As we know, accelerating only digs the wheel deeper into the ground in both cases.

Saturating the sand with sea water somehow makes the sand firm enough to hold the weight of the wheel and soon enough the vehicle is freed. ->> *Hydrocompaction*.

This is a commonplace solution that is done almost without the thought that Soil Mechanics principles are involved.

The solutions to the foregoing case studies all have something in common, and that is a clear understanding of the behavior and physical characteristics of the soil and application of Soil Mechanics to the solution of **“simple”** Earthwork Problems.

As is often the case, problems such as these have occurred in the field countless times without being correctly identified and thus have resulted in significant losses to the contractor, delays in the projects and substandard quality of compacted Earthfill.

Again, it must be qualified that it is not only the contractor who is to blame but also the Consulting Engineer in most instances for this state of things. Our only consolation is that the problem is not only unique to our country but also even in more advanced Western Countries.

A vigorous search of various Soil Mechanics and Foundation

Engineering Books yielded only fleeting or sporadic references to these common problems we encounter in day to day Earthwork Construction where soil mechanics principles are applied.

We however would still recommend review of various literature on the subject for those who wish to have a deeper understanding of the problem at hand particularly with the advances in the *state of the Art and the State of Practice of Soil Mechanics*.

8 APPLICATION OF KNOWLEDGE GAINED

However, it is not only enough to know how to select the proper compactor for the job. It is also important to use this in conjunction with our knowledge of Soil Mechanics principles which we now apply:

8.1 Sands and Clean Coarse Grained Soils

Vibratory compaction works best. However, we should aid this by liberal application of water immediately ahead of the vibratory compactor. Remember, coarse grained soils compact best at the very very wet condition "**P₂**" or at very very dry condition "**P₁**". Water serves as a lubricator but its total absence also prevents capillary forces from impeding the rearrangement of soil grains into a denser packing. Speed of the vibratory compactor is also important and needs to be controlled to about 2 to 4 KPH. Vibratory frequency is also essential and should nearly approach the natural frequency of the soils. Standard frequencies are in the range of 30 to 40 cps.

The static weight of the vibratory roller is also important since the dynamic force exerted on the soil is a function of the static weight. The wheels of the roller are either ballasted by water, sand or even slag in order to increase the static mass.

Because the vibratory roller causes an "**advancing wave**" on the top of the lift being compacted, Field Density Testing in order to be fair has to be done below this disturbed layer. It will normally be required to scrape the top 50 cms before seating the Field Density Plate in order to be able to test the actual condition of the specific lift.

Field Density testing using the Sand Cone Method (**ASTM D-1556**) requires extra care since the means to measure the volume is calibrated clean sand. Any jarring motion results in increased sand intake of the test hole resulting in bigger hole volume computed than the actual resulting in low compacted densities. This condition can also be caused by compaction equipment being allowed to operate very near a Field Density test in progress.

In one project, a bull headed contractor's foreman could not be prevailed upon to stop his operations while tests were being performed nearby. He only relented when a series of "**Failing**" FDT results made him realize his mistake.

Back to the subject of moisture content, for clean coarse

grained sands, moisture is irrelevant except for the total absence of it or its presence at saturation levels.

Thus, there is no such thing as an **Optimum Moisture Content** and proctor criteria are entirely inapplicable in this context.

8.2 Clays and Intermediate Soils

For Fine Grained Materials and intermediate soil types possessing significant plastic fines, sheepsfoot rollers or pneumatic tired rollers are best. The kneading action allows reorientation of the grain and allows expulsion of entrapped air.

The sheepsfoot was modeled really after the shape of a sheep's foot perhaps based on the observations of **Mr. Mc Adam**. The tendency of the sheepsfoot is to walk-up by progressively compacting or densifying the lowermost layers first and walking upwards. Thus we see that topmost layers are slightly less compacted and therefore need to be bypassed when conducting a Field Density Test.

In stark contrast to clean coarse grained soils, compaction moisture content and the **Proctor criteria** are fully applicable and the control of moisture during compaction is a crucial factor in the attainment of proper compaction.

Static weight is also important as it increases penetration of the sheepsfoot and increases the force pressing the platelets together.

Speed is not so critical as it is the kneading action and coverage that is important.

Vibratory motion is not necessary and is in fact harmful as it can cause build up in pore pressures in the soil and also cause shear cracking.

8.3 Lahar

Since *Lahar* is a byword in Central Luzon and since billions will be spent in Lahar Protection Structures, using Lahar as the primary construction material, it may be worthwhile to consider this as a separate material for this paper.

Although Lahar possesses some fines, the fines are non plastic and consist of very fine ash particles.

Lahar drains easily and compacts readily as proven by river crossings which become passable as soon as the flood of Lahar subsides.

From this, we can already infer that Lahar behaves like a clean coarse grained material that it is.

Thus, Lahar is most sensitive to vibratory compaction and could compact well at **very very dry** or **very very wet** condition. Moisture control is unimportant except to see to it that either we have none of it or plenty of it during vibratory compaction.

We have done several tests on Lahar as a matter of research interest and our conclusions are as follows:

1. Lahar behaves as a perfectly granular material.
2. Lahar responds well to compaction even under ordinary vehicular loading and therefore the passage of construction traffic alone could assist compaction.
3. Lahar possesses high initial CBR value but some degradation in the CBR strength occurs if the sample is aged at saturation conditions (*this is probably due to breakdown in the ash coating the individual grains*).
4. Significant sulfate levels were present (*at least during the initial discharge*) which could impair the integrity of Portland cement concrete when this is used as fine aggregate.

We have noted that several tests have been performed by some agencies which show the all too typical bell shaped curve and therefore an Optimum Moisture Content. However, it would be noted right away that compaction started at moisture contents of 3% or greater and thus the Peak “**P₁**” remained undetected leading to erroneous conclusions and the unnecessary imposition of an **Optimum Field Moisture Content**.

9 CONCLUSIONS

The purpose of this paper would have been already truly served if the construction industry would start to recognize the differences in behavior between coarse grained and fine grained materials through the use of sound fundamental Soil Mechanics principles rather than from “**feel**” or guess work.

Often times, these fail in the actual field situation and the simple task of Earth Compaction becomes a costly and heartbreaking exercise.