SOIL MECHANICS PRINCIPLES APPLIED TO EARTHWORKS

1.0 INTRODUCTION

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 dishearthening 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:

1.1 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 incured 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.

1.2 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?

1.3 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 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.

1.4 Stalled Vehicle Wheel

A hypothetical but common case which involves a car wheel stuck in a hole 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.

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

The solution to the foregoing case studies all have something in common, and that is a clear undestanding 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 occured 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.

It is the intention of this paper to unify and integrate references to these in various literature on this topic to provide a more **"concentrated"** understanding of Fundamental Soil Mechanics Principles as applied to Earth Compaction and Earthworks in General.

2.0 THE MECHANICS OF SOILS

In order to successfully apply Soil Mechanics to the solution of our Earth Compaction problems, it would be necessary to have a clear understanding of the fundamental principles.

However, for this paper we shall only limit ourselves to a clear understanding of **Particulate Mechanics** or the behavior of soils as discrete particles when acted upon by various forces such as gravity, vibration or impact, water and seepage or combinations of these forces.

We shall strive to make the problem as simple as possible even to the layman in order for him to have a fundamental grasp. We however would recommend review of various literature on the subject for those who wish to have a deeper understanding of the problem at hand.

3.0 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**

- **o Fine Grained *(clay)* or Cohesive**

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

4.0 SOIL SHEAR STRENGTH

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 soils' **Shear Strength** 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 particulate character.

Depending on the granulometry of the soil, the shear strength is either derived from electrical and chemical forces of attraction *(cohesion)* and repulsion as in days or by simple 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 by cementing it which is sometimes resorted as in soil cement if good materials are not readily available.

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."**

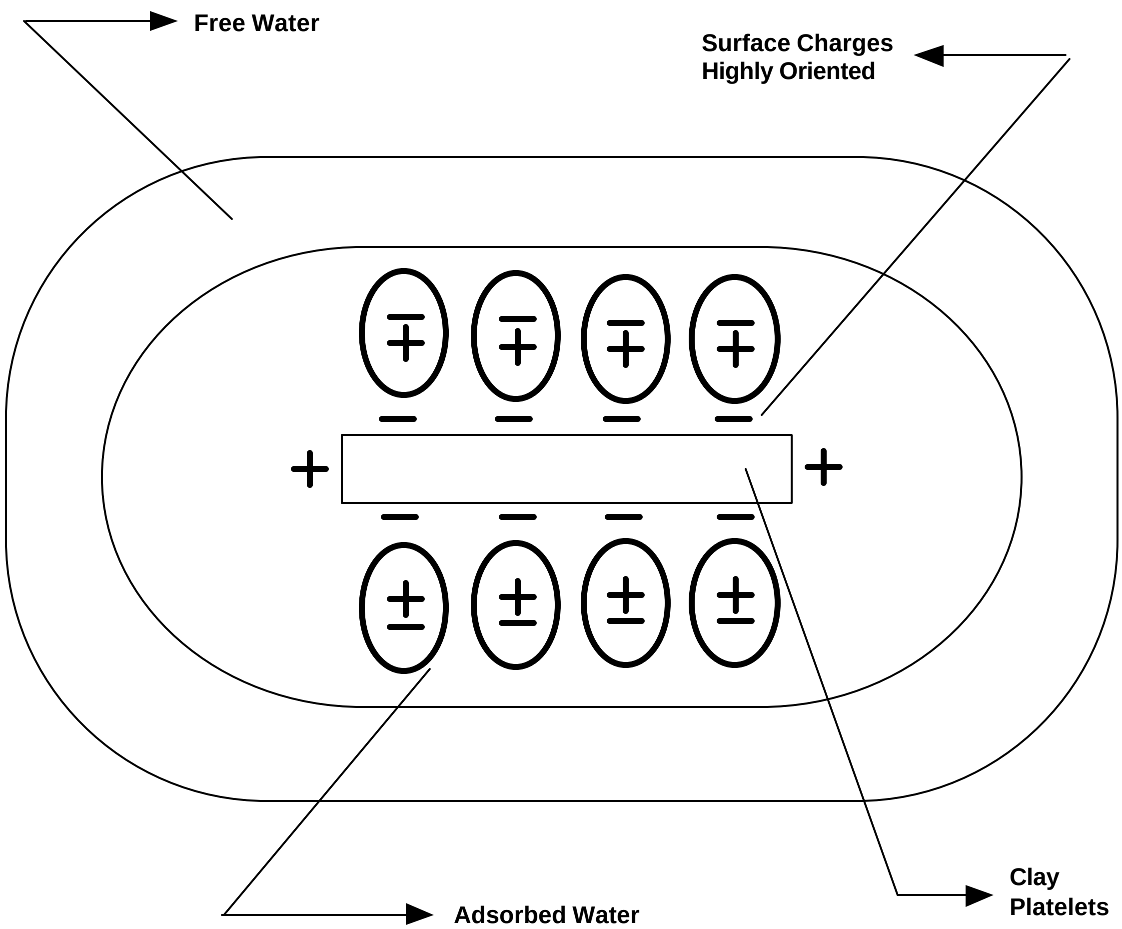
As we shall see later on, reduction of interparticle distances would sometimes require addition of more water into the soil in order to dislodge more water. This statement appears to be confussing but its proof reiterates the importance of the understanding soil particulate behavior in the solution of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

5.0 MICROSTRUCTURE

5.1 Clay Microstructure

Let us now peer again at our microscope to look at a sample of cohesive or fine grained clay soil .

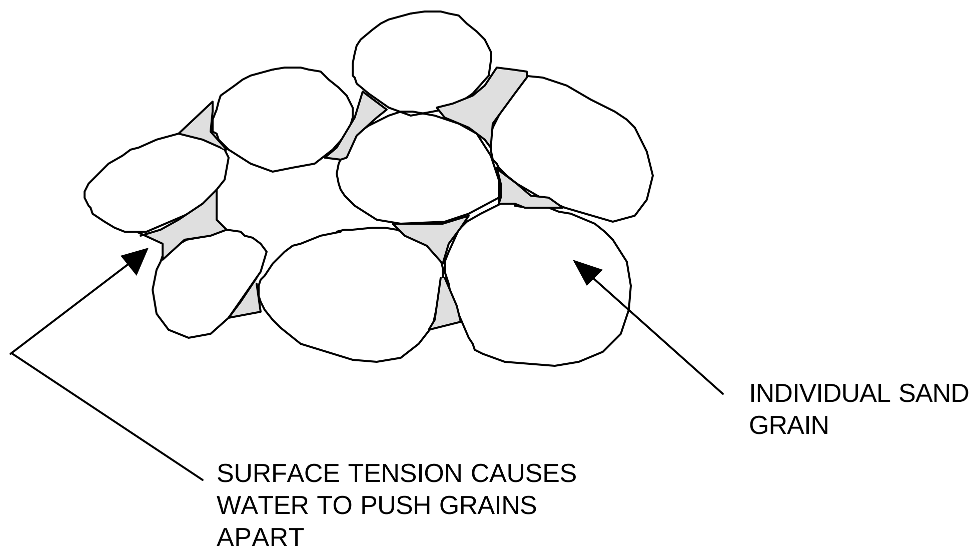
Individual Clay Platelet



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 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 dislodged or remove the adsorbed layer. However, the loosely held water can be removed in the field by sample air drying or windrowing. Once the free water is removed, compaction can be attained. The particle orientation as we shall see in the succeeding table also affects some other physical performance characteristics of the soil.

5.2 Sand Particles

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



A very dry sand in the hand can not be squeezed into shape whereas a 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 **Hydrocompaction.** Perhaps only the mechanism behind it is not well understood.

5.3 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 have the platelets more or less aligned to each other.

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

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 $(k_l > k > k_p)$ [1]
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', ø'	similar	similar
A-factor at failure	negative	not as negative

[1] **k_l 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 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.

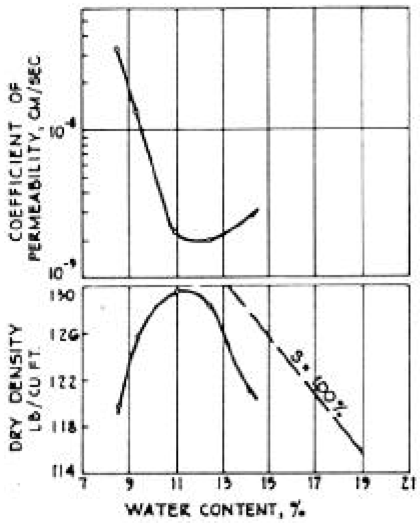
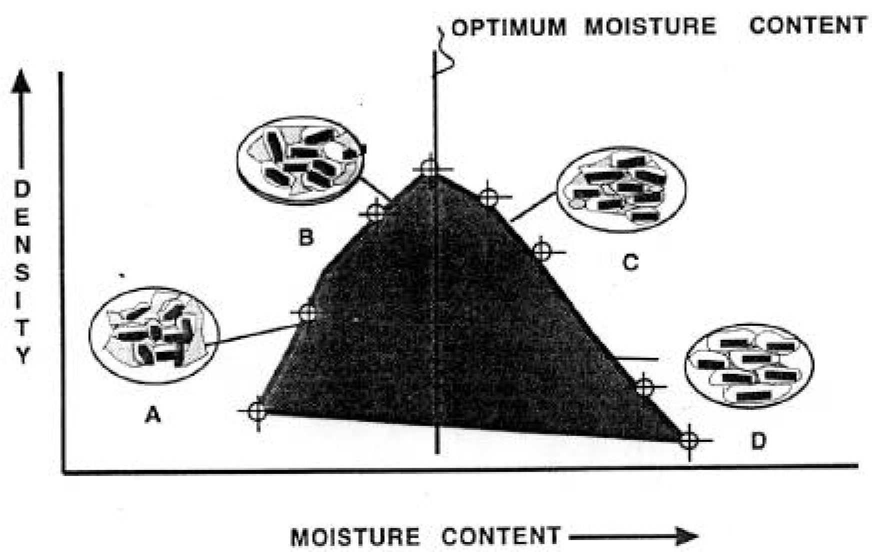


Figure 8.5 Effects of compaction water content on soil permeability. (After Lambe, 1958.)

6.0 MOISTURE DENSITY RELATIONSHIPS

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



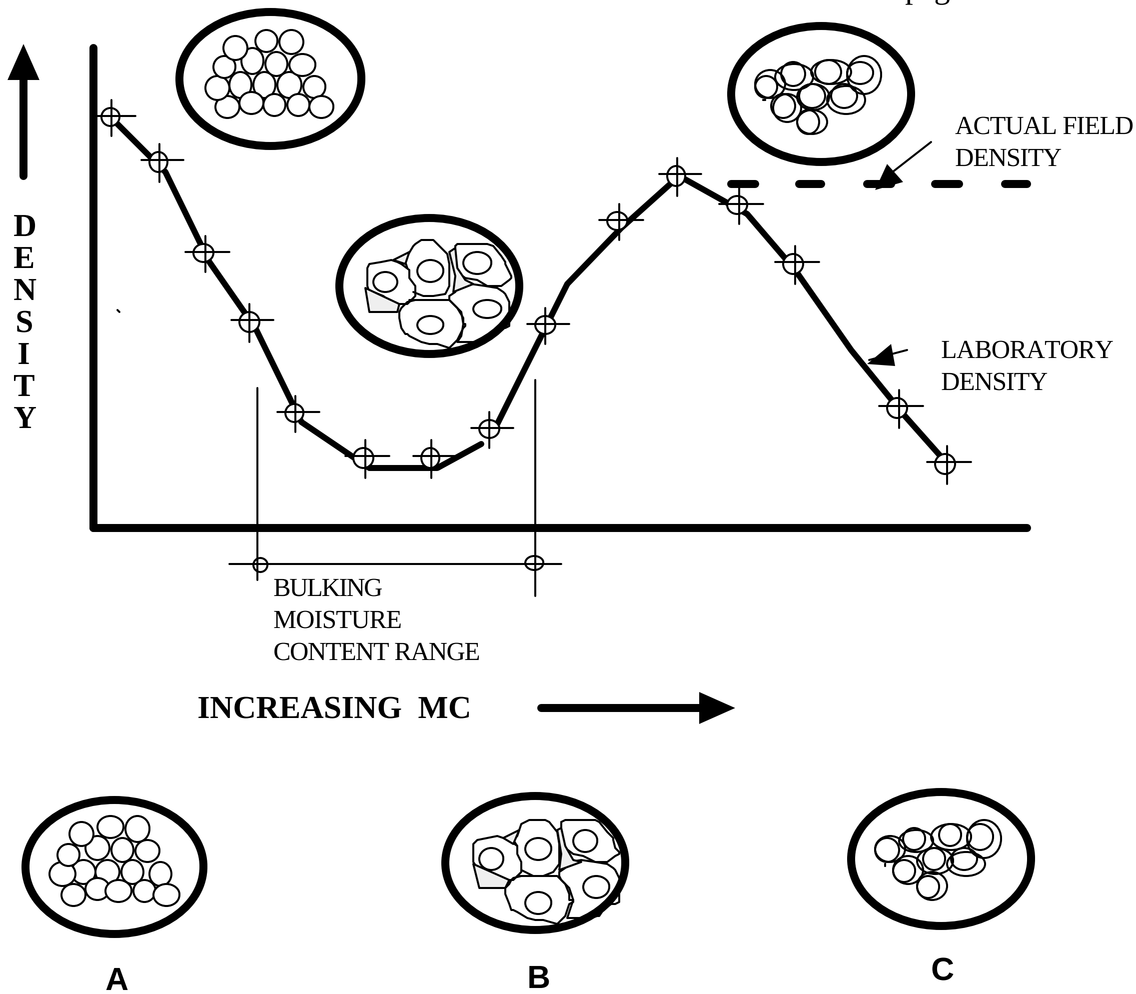
Out total familiarity with this simple **bell shaped curve** and its universal acceptance as the *"characteristic"* compaction curve has caused most of the problems we encounter today in Earthworks compaction. Too often, it has not been realized that this is not the only shape a laboratory Proctor curve 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 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 aditional water beyond this point results 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.

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

We see right away that the Moisture Density curve indicates two density Peaks **“P_1”** and **“P_2”** where density is high. The first Peak **P_1** occurs when the soil is very very dry **(MC ‘ O)** and the other Peak **P_2** 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 **"P_2".** 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 can not 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 **P_1 & P_2** 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.*

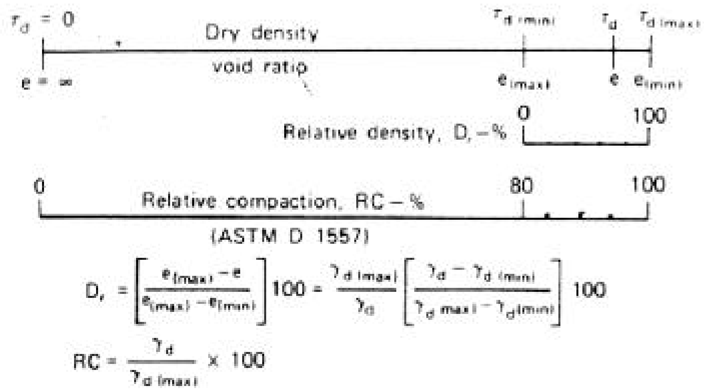


Figure 8.9 Relative compaction–relative density relationships. (After Lee and Singh, *9th Annual Engineering Geology and Soils Engineering Symposium*, Boise, Idaho, 1971.)

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 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.

6.0 COMPACTION EQUIPMENT

Having recognized the behavioral characteristics of soils *(Particulare 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 contact are best compacted by causing a jarring motion such as what a vibratory roller would impart.

- Fine Grained 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.

We now look at the Chart below to determine the range of applicability of various compaction equipment:

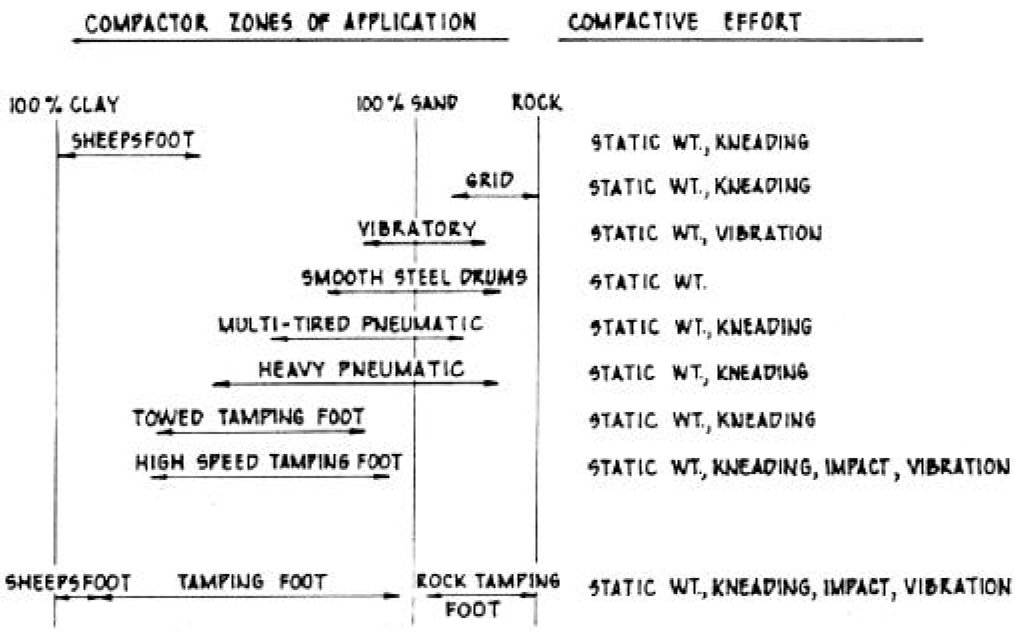


Figure 8.10 Compaction equipment selection guide. This chart contains a range of material mixtures from 100 percent clay to 100 percent sand, plus a rock zone. Each roller type has been positioned in what is considered to be its most effective and economical zone of application. However, it is not uncommon to find them working out of their zones. Exact positioning of the zones can vary with differing material conditions.

We can therefore see the effective range 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.

However, it would be shocking to know that in a big project inside a U.S. Base, the Earthworks subcontractor was unable to compact the highly plastic soil despite repeated passes. Several weeks of reworks have passed before we realized that the contractor was using a Vibratory Roller on a clay soil. Over vibration of the clay soils had in fact caused the formation of Shear Cracks causing weakening of the soil! When the compactor was changed, the problems of the contractor vanished.

7.0 APPLICATIONS 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:

7.1 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 **"P_2"** or at very very dry condition **"P_1".** 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 is entirely inapplicable in this context.

7.2 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 modelled 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 coarsed 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.

7.3 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 possess 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 possess 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 **"P_1"** remained undetected leading to erroneous conclusions and the unnecessary imposition of an **Optimum Field Moisture Content.**

8.0 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 Soil Mechanics principles rather than from **"feel"** of guess work.

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