Field Compaction versus Lab Compaction; New Advancement

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SUMMARY

With the advancement of technologies, it is critical to better understand the behavior of field compacted soils for improved quality control in the field. Standard laboratory compaction tests for soils (a three-phase material) are often viewed as the compaction standard for earthen fills. These dynamic compaction laboratory tests apply constant compaction energy to a small volume of confined soil which doesn't represent the field condition. Based on field and laboratory studies it has been proven that the field compacted soil behavior is different from laboratory compacted soils. Hence technologies have been developed in recent years to better represent the behavior of field compacted soils.

INTRODUCTION

Compacted soil (three phase material) behavior depends on several factors including the soil type, moisture content and the method in which energy (type and amount of compaction energy) is transferred to the soil. When energy (equivalent to force x displacement or stress x strain) is applied to the soil, it is transformed into to normal and shear stress to overcome the resistance to particle movement in the soil. Since the behavior of compacted soil is very much dependent on the particle arrangement (soil structure); the stress-path history (how compaction energy is delivered relative to progressive moisture-density relations), applied energy used during the compaction (amount of stresses repeatedly applied to move the soil particles) and compaction state (relative to optimum moisture-density relations) is very important (Holtz et al. 2010, Vipulanandan et al. 2007-2011). As soil structure dictates strength and stability, soil structure is dictated by stress path, cumulative compaction energy, and compaction state. This phenomenon was first observed by Lambe in 1958.

Compaction efficiency of soils is also important. Compaction efficiency is a function of soil properties relative to compaction methods. For example, well graded soils compact more efficiently than poorly graded soils, clayey soils compact more efficiently with non-vibratory kneading compaction, coarse-grained soils compact more efficiently with vibratory compaction, unconfined compaction is more efficient than confined compaction, etc.

Soil compaction in construction is significantly different than compaction in laboratory tests. The similarities and differences between field and laboratory compaction are summarized in Table 1. It is clear that all of the laboratory and field conditions are different, except for the soil (solid particles in the soil). Hence based on compaction conditions alone, the behavior (i.e., strength, stress-strain behavior, climatic/load stability, etc.) of field compacted soils will be different from laboratory compacted soils. Further, these differences between lab and field compaction are compounded by field/lab differences in stress path, cumulative energy, and compaction states, even when compacted in the same moisture-density space.

(a) Dry Density-Moisture Content Space (γ_d - ω Space)

As shown in Fig 1, a soil that is compacted uniformly in construction will only compact along the field moisture-density relations generated by Compactor A with a soil-lift combination. A moisture-density plot resulting from a standard lab compaction test of the same soil can also be superimposed on the same moisture-density graph, as illustrated. Since moisture-density plots (locations) resulting from standard lab compaction tests vary for the same soil, this illustration reflects one example test result superimposed. The Figure shows how erratic lab compaction curves can vary from the actual compaction curves in lift construction. If the magnitudes of field and lab energy are close enough, lab curve results will often intersect the field curve at some point along each curve. In this example, the two curves intersect at Test Point A where the soil exhibits the same dry-density (γ_d), moisture content (ω) and void ratio (e). However, the common Point A would clearly result from two different stress paths from field compaction and lab compaction. Soil compaction in construction (**Path #1** and **Field Compactor A)** and in the lab **(Path #2** and **Lab Compactor B**) on respective paths of each to Point A, involve different methods, magnitudes, conditions and moisture-density relations resulting in two different compaction states and soil structures. Clearly, Path #1 compaction would result in wet-side of the field optimum and Path #2 compaction would result in the dry-side of a particular lab test optimum. Because the stress paths, compaction states and soil structures are greatly different, the mechanical properties of each path at Point A will be greatly different.

Table 1 – Basic Comparison of Laboratory and Field Compaction Parameters

Variables	**Mixed-Scale Laboratory Compaction**	**Full-Scale Field Compaction**	**Comparison**
Type of Soil (Solid particles in the soil)	Same	Same	Same solid particles
Total Cumulative Energy	Fixed	Variable, Depends on the compactor, soil, lift combination	Different
Type of Cumulative Energy	Impact (dynamic)	Different, Depends on the compactor	Different
Type of Stress	Dynamic Stress	Quasi-static stresses	Different
Volume of Soil	Limited	Unlimited	Different
Condition of Compaction	Confined	Unconfined	Different
Lift thickness	1/3 mold height	Variable	Different
Number of passes	Fixed blow counts	Variable	Different, though both are compactor-specific & designed for full compaction
Maximum Dry Density	Depends on the soil, test selection & test variables	Depends on the soil, compactor, # of passes and lift thickness	Different
Optimum Moisture Content	Depends on the soil, test selection & test variables	Depends on the soil, compactor, # of passes, and lift thickness	Different

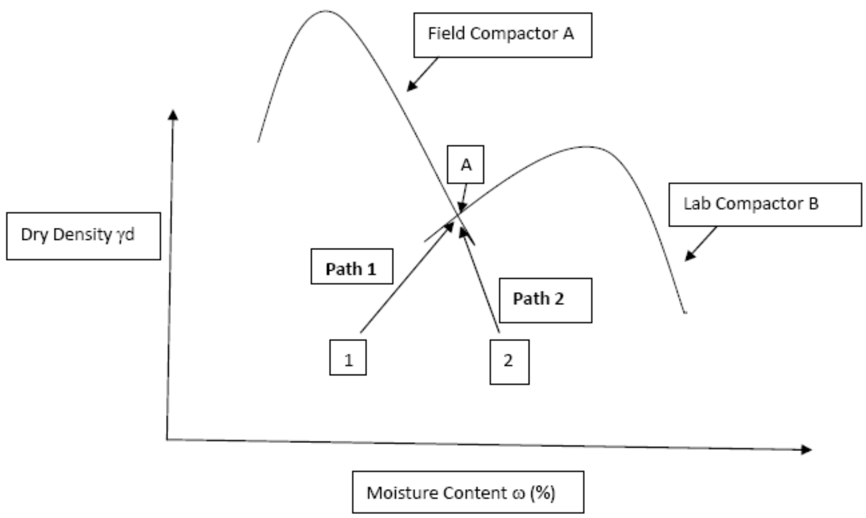


Figure 1 - Compacted Soil Properties Depend on the Energy/Stress Path of Compaction

(b) Simplified Analogy to Soil Structure (Soil Particles represented by bricks)

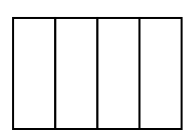
Let's assume the size of each brick is 4" (length) x 3" (width) x 2" (height). Assume a compressive strength of 100 psi. The weight of each brick is M and the Volume is V (24 cubic inch).

Take four bricks:

1 2 3 4

How should the bricks be arranged? What is the Maximum Load? For purposes of this analogy, let's use compactors A, B & C to arrange the bricks, and look at bearing loads only at constant density.

<u>Case 1: Field Compactor #A</u>

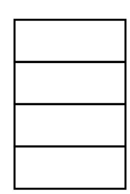


Total Weight = 4M, Total Volume = 4V…. Unit Weight = M/V

Cross sectional area = 4x2x3 = 24 sq.in

Maximum load carried = 100 x 24 = 2400 lbs.

<u>Case 2: Lab Compactor #B</u>



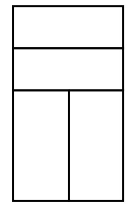
Total Weight = 4M, Total Volume = 4V…. Unit Weight = M/V

Cross sectional area = 4x3 = 12 sq.in

Maximum load carried = 100 x 12 = 1200 lbs.

Case 3: Compactor #C

Total Weight = 4M, Total Volume = 4V…. Unit Weight = M/V



Cross sectional area = 4 x 3 = 12 sq.in

Maximum load carried = 100 x 12 = 1200 lbs.

(1) Will the Cases 1, 2 and 3 have the same density? Yes (Same total volume and weight).

(2) Will Cases 1, 2 and 3 have the same strength (axial load capacity)? No.

Why? The structure is different. Even though the density is the same, the strength depends on the structure. (Obviously, endless variations of brick structures including angles, contacts and load variations have been ignored for simplicity for purposes of this analogy.)

Summary: The type of compactor and stress path history (how the energy was delivered) dictated the brick arrangement and hence the maximum load capacity. Hence the unit weight does not indicate soil structure, is not the only property that indicates or influences the behavior of the brick structure, and does not dictate its strength and stability.

(c) Hypothetical/Special Case:

(i) Can a field density be the same as a laboratory density?

Answer: Yes.

(ii) How? By uniform compaction of a lift using the moisture-density relation produced by a select compactor, lift thickness and number of passes; or by trial & error with compactors, moisture and passes, with or without uniform compaction.

(iii) Will the other properties be the same? No

(iv) Why? Because of the stress path (how the incremental energy was delivered in the laboratory and the field) and the ultimate compaction state and soil structure. (example: Compare Compactor A (Lab) to Field (Compactor B)).

(d) Soil Structure versus Stress-Path

Questions and Answers:

(1) Question: What is soil structure?

Answer: It is how the soil particles are arranged in the compacted soil. Lambe (1958) studied effect of compaction on the structure of soils and the findings are shown in Fig. 2.

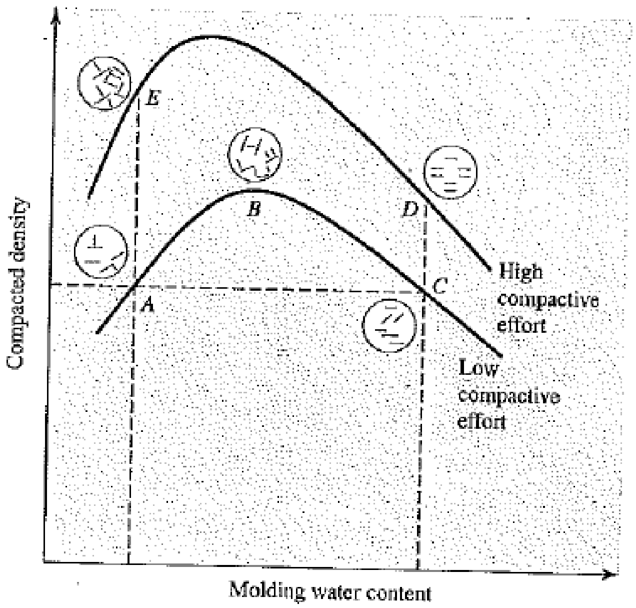


Figure 2 - Effect of Compaction on the Soil Structure (Lambe (1958)).

When the clay soil is compacted with a moisture content dry of optimum, particles form a **flocculated** structure based on the compaction effort (total and incremental energy, and stress path). When the moisture in the soil is higher, near optimum and wet of optimum, compaction helps with the formation of a more **dispersive** soil structure.

(2) Question: What does the moisture (ω) do?

The moisture in the soil influences the diffusion double layer in the clay particles and also helps with the **lubrication** of the soil particles. Lubrication is enhanced by the excess moisture in the soil. Lubrication helps with the particle movement.

(3) What does a Compactor Do?

It transfers energy to the soil under its own weight and mobility. The weight of the compactor and mobilization energy applies vertical stress (σ_v) to the solid particles in the soil. Roller configuration is a key factor to mobilization energy and compaction.

(4) How is the compactor energy transferred to the soil?

The energy is transferred to the soil by applying normal and shear stresses to the soil and moving the solid particles. The type and magnitude of the stresses applied will very much depend on the compactor.

(5) Incremental Energy (ΔE) versus Total Energy (E) versus "Full Compaction"

The energy is applied to the soil incrementally (every pass), as are the resulting stresses. Based on the applied incremental energy and stresses, **the soil particles will be moved to form or build a stable soil structure**.

Based on the incremental energy applied by the compactor to the soil during each pass, the stresses developed in the soil particle will vary progressively with the movement of the particles. (Energy applied to soil = Force (stress) transferred to soil x displacement of the particles). Hence the incremental energy applied to the soil for compaction directly correlates to the stress path (stresses applied to move the soil particles).

Total energy (E) applied to the soil will be the accumulation of all the incremental energy (ΔE).

"Full Compaction" is considered to be reached when the change in soil density is asymptotic with additional roller passes. At this point, moisture-density relations have stabilized (from progression up its respective line-of-optimums) and soil particles have formed a stable structure along that moisture-density relationship.

(6) What is Stress-Path?

It is the stresses applied to the soil at every stage of compaction to build a stable soil structure. The stress path for compaction will be influenced by the incremental energy applied by the compactor, the compactor type, soil type, and compaction conditions.

(7) With the Same Moisture Content and Compactor can I Get Different Densities?

Yes. See Figure 3 for illustration and pathways. The Figure shows compaction starting with a soil state at Point #1. Higher density (Point #2) is then achieved with 4 passes of the compactor at the same moisture content. Density is increased further to Point #3 with 4 more passes (8 cumulative) of the compactor at the same moisture content. At 12 passes, density is further increased at the same moisture content. This figure also illustrates the progression of moisture-density relations with increasing compaction energy. Note how compaction curves progress up the respective line-of-optimums with increasing energy, and how the progression slows as compaction reaches an asymptotic point. Note how Point 2 is at a dry-of-optimum state, Point 3 is at optimum, and Point 4 is wet-of-optimum. Increasing compaction energy moved the soil compaction state from the dry-side to the wet-side of optimum. It is the stresses applied incrementally to the soil at every stage of compaction that helped to achieve the higher densities. The stress path for compaction will always be influenced by the incremental energy applied by the compactor.

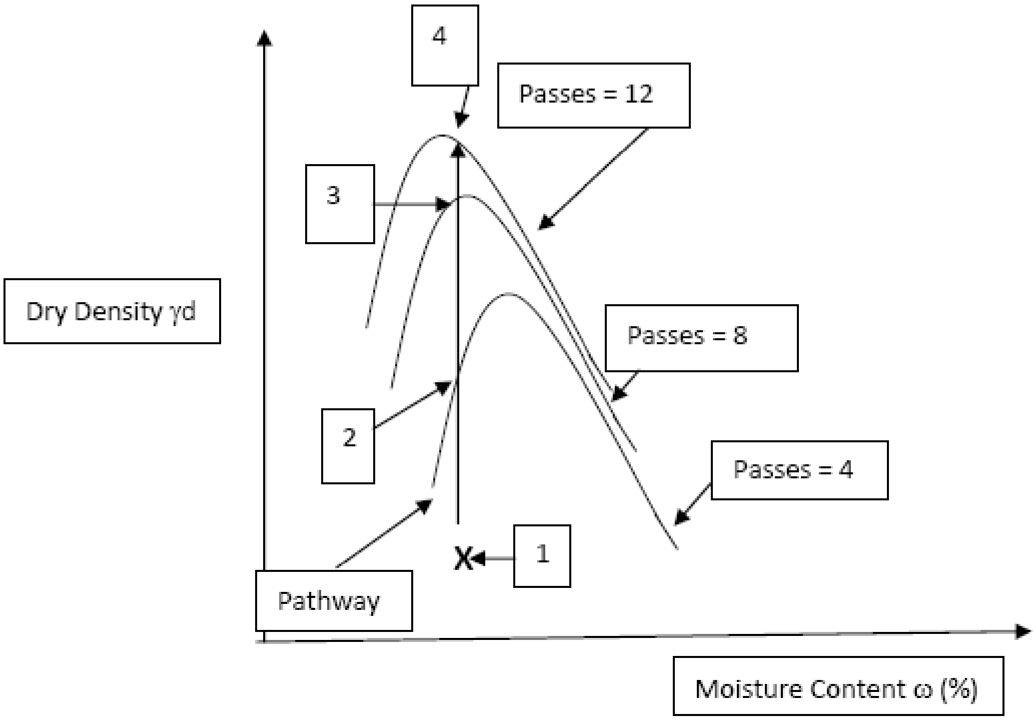


Figure 3 - Compaction with the Same Compactor and Moisture Content to Achieve Higher Densities

REFERENCES

Holtz, R., and Kovac, W.D. and Sheahan, T. C. (2010), An introduction to Geotechnical Engineering, Prentice Hall, Inc.

Lambe, T. W. (1958a), "The Structure of Compacted Clay, "Journal of Geotechnical and Foundation Division, ASCE, Vol. 84, No. SM2, 1654-1 to 1654-35.

Lambe, T. W. (1958b), "The Engineering Behavior of Compacted Clay, "Journal of Geotechnical and Foundation Division, ASCE, Vol. 84, No. SM2, 1655-1 to 1655-35.

Langston, R. and Tritico, P. (1995), Practice Improvements for The Design and Construction of Earth Fills, Proceedings, ASCE –Texas Section.

Mokwa, R. L., and Fridleifsson, S., (2007), Earthwork Compaction Evaluation Using Soil Air Voids, Canadian Geotechnical Journal, Vol. 44: pp.151-159.

Nagaraj T. S., Lutenegger, A. J., Pandian, N. S., and Manoj, M., (2006), Rapid Estimation of Compaction Parameters for Field Control, Geotechnical Testing Journal, Vol. 29: No.6, pp. 1 -10.

Vipulanandan, C. (2011), Field Compaction Verification Using a New Surface Penetrometer (SP-CIGMAT) During Construction, Proceedings, Geo-Frontier 2011, ASCE Geo Institute, Dallas, Texas.

Vipulanandan, C., Guezo, Y.J., and Bilgin, O., (2007), Geotechnical Properties of Marine and Deltaic Soft Clays, Proceedings, Geo Denver, Denver, USA

Vipulanandan, C., Guezo, Y.J., and Bilgin, O., (2007), Stress and Stress Path Dependence of Recompression (Cr) for an Over Consolidated Clay Soil, Proceedings, CIGMAT-2007, Houston, Texas (http://cigmat.cive.uh.edu)

Vipulanandan, C., Kim, M.S., and Harendra, S., (2007), Microstructural and Geotechnical Properties of Houston-Galveston Area Soft Clays, Proceedings, New Peaks in Geotechnics, ASCE Geo Institute, Denver, Colorado