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RAMCODES Method for Compacted Soil Design: Development and Applications

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Abstract. This paper submits a practical and applicable whole approach to compacted soil design, proved in actual projects. This approach is called the RAMCODES method for compacted soil design (CSD) which is supported by three main pillars: the design curve, the design pyramid and the QA/QC quadrants. The last of the pillars will be explained in a future work due to space limitations at this time. For RAMCODES, designing a compacted soil is the determination of the minimum degree of compaction at which the soil exhibits a requested response under specific conditions of hydration, surcharge and loading rate. This is carried out using a design curve which is a plot that relates a soil compaction degree to its response under constant hydration, surcharge and loading rate conditions. RAMCODES CSD uses a performance-based criterion to achieve a compacted soil design using several analyses techniques. This method allows the designer to design a soil by the simple method or by the composed method which produces a weighted average-strength value regarding several hydration conditions along the design-year. In this paper, the risks and economic implications of designing with code-driven criteria in lieu of performance-based criteria are explained using a conceptual construction called the RAMCODES pyramid of design. Present paper introduces the development of the method and applications of RAMCODES CSD to real projects.

Keywords. Soil, compaction, Proctor, CBR, RAMCODES, strength, roads, embankments, design.

1. Introduction

RAMCODES is an acronym for rational methodology for compacted density and strength analysis of geomaterials. This approach has been developed over time by the author since 1998, with the financial and technical support of Venezuelan SOLESTUDIOS Foundation, and applied to geomaterials such as bare soil and bituminous mixes [1-6], as an improvement on classic design methods such as California Bearing Ratio (CBR), Marshall, and Superpave. RAMCODES is based on three topics, namely, soil mechanics, statistics, and weight-volume relations. Previously, this methodology has produced three tools for the analysis and design of geomaterials, such as, the gradation chart for asphalt mixes [5], strength maps for compacted soils [3], and the polyvoids for asphalt mixes [4,6].

This paper submits a practical and applicable whole approach to compacted soil design, proved in actual projects, as shown.

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2. Background

In soil compaction technology, the decade of 1955 to 1965 is considered the "golden era" in this important topic of civil construction because the works of researchers as [7-10], permitted the understanding of the soil compaction physical phenomenon and its relation to the mechanical and hydraulic behavior of the soil. Also, with the emergence of unsaturated soil mechanics since 1990, the advances in testing devices and computer software, researchers like [11], and [12], demonstrated the strong influence of the suction of the soil on the development of the strength of the soil on compaction, permeability of the soil, loss of strength of the soil due to wetting, implications of submergence, volume change of soil, liquid waste transport through the mass of soil, and many other elements of cause. Furthermore, the development and application of this science continues since there are still many facets of compacted soil phenomena to be understood. However, by the experience of this author as a consultant, present practice for soil compaction design and specification is a very limited version of the golden era while the recent advances in soil compaction science are applied only to a number of privileged projects, and a standard procedure for soil design under these modern concepts is not yet established. This author is very concerned by the fact that the principal civil projects in Venezuela [13]; and the state of the art in structural backfill construction in the United States of America [14], are based on the compliance with a field density of 95 to 100% of Proctor test for soils with fines or fine soil, and a certain value of relative density for clean soils, as a simple recipe to obtain structural backfills with acceptable engineering properties; but surprisingly, not requiring any performance verification.

Furthermore, at present time there is neither a standard procedure for compacted soil design in respect of recent advances in compacted soil design from the unsaturated soil perspective, nor an approach that takes into account the vulnerability of the several criteria for compacted soil specifications that exist in present time. This paper presents both a proposal to organize such criteria and their relationship to the vulnerability of design with regard to the uncertainty over the performance of the soil under a range of hydration, surcharge, and loading rate conditions; and a method for designing a compacted soil under the lowest vulnerability to failure. All of the above criteria are included in the RAMCODES Compacted Soil Design (CSD) method.

3. Development

The RAMCODES CSD method is intended for soils whose strength is susceptible to wetting, such as soils with plastic fines as GM, GC, GC-GM, SM, SC, SC-SM, commonly used in road embankment and structural backfilling construction.

3.1. Philosophy of design

As for RAMCODES in road embankment and structural backfilling construction, quality assurance (QA) means to design a compacted soil, while quality control (QC) refers to field testing on compacted lots for QA statistical verification (i.e., Design requisites).

Designing a compacted soil means the establishment of a minimum degree of compaction (%C) sufficient for soil to exhibit the desired response, typically a mechanical or hydraulic response; under the particular hydration, overburden pressure and loading rate conditions of the project. This analysis usually comes either from laboratory, field, or both; testing programs. RAMCODES CSD is based on four key concepts: the design curve, which relates to the degree of soil compaction to performance under studied conditions; the design pyramid, which establishes a hierarchical order among the different compacted soil design approaches; the QA/QC quadrants that present all possible combinations of QA (compliance vs. performance) and QC (deterministic vs. probabilistic) approaches, and quantitative soil classification. Due to limitations on space, only the first two concepts will be presented in this paper.

3.2. Design curve

By definition, a design curve is a trendline that shows the relation between the degree of soil compaction and the corresponding response of the soil studied, under constant hydration, surcharge and loading rate conditions. For fine soils, or coarse soils with fines, the degree of compaction is expressed as a percentage of the Proctor test maximum dry density; while for clean soils, the compaction degree is quantified by the relative density value.

The compacted soil studied response is typically a strength parameter (i.e.,CBR, friction angle, Elasticity modulus, and accumulated plastic deformation), but it could also be attributed to the permeability of the soil.

The hydration condition of the compacted soil refers either to the degree of saturation, or to soil suction when tested. This condition could be achieved from any hydration or dehydration path, like: wetting, drying, drying-wetting cycles, acquainted by an amount of suction lost or gained; or also could be related to the as-compacted condition.

Surcharge is the confinement pressure around the specimen of soil, achieved either isotropically or anisotropically.

The reader may notice that both hydration-dehydration and confinement pressure changes constitute the stress history of the soil. However, in compacted soils for road pavements, and backfills, with regard to their amounts, the changes in the stress history are more likely related to suction changes, rather than surcharge pressure changes.

Finally, the rate of loading can be low—commonly known as “static” or “monotonic—which is related to slow-motion traffic, or loading in building foundations. Also, the rate of loading can be high—known as “dynamic” or “cyclic”—as in road high-speed lanes, or in backfills for reciprocating machinery foundations.

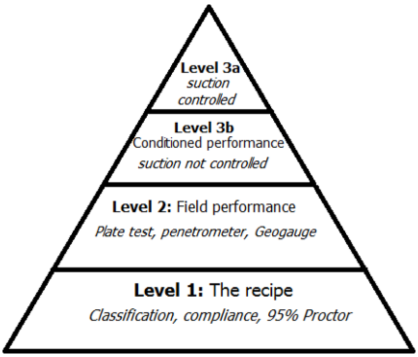

Figure 1. RAMCODES CSD Pyramid of design.

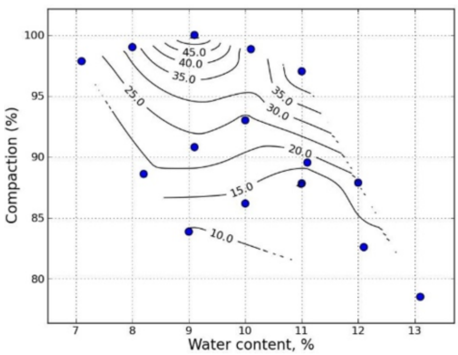

Figure 2. Strength map for CBR value.

3.3. The Pyramid of design

The RAMCODES CSD Pyramid of Design is a three-level triangular figure that establishes a hierarchical relationship between the different criteria that exist to compose the specification for a compacted soil (see Figure 1).

According to the RAMCODES CSD Pyramid, there are two criteria to design a compacted soil, namely: compliance (Level 1), and performance (Levels 2 and 3).

The compliance criterion refers to the fact that soil material must meet a minimum quality based on classification (i.e., gradation, plasticity, coarse particles soundness), and compacted lots must meet a minimum degree of compaction to the Proctor test (typically 95 percent to 100 percent of Proctor's maximum dry density), or a certain minimum value of relative density. Because a compliance criterion is not related to performance, there is no way of assuring that the compacted lot will exhibit the engineering properties required for structural security, accordingly to the standards of the project. During his seminars, this author refers to the compliance criterion as The Recipe, and it should only be used in civil projects of a relatively low importance. As a matter of fact, Professor Iraj Noorany, from San Diego California University, uses the term code-driven to refer to specifications with roughly the same description of The Recipe specifications.

At Level 2 of the pyramid, soil material is specified the same as at Level 1, but it is also required that the compacted soil exhibits in the field at the very least, the response value requested by the project, and that is why that is called "Field performance". There are two alternatives for achieving this: a direct measurement and an indirect measurement. The direct measurement is performed on the compacted lot to determine the response of compacted soil. Typical tests for direct measurement of compacted soil strength are the plate tests, the dynamic cone penetrometer, the field torvane test, Humboldt Geogauge (a portable device to measure response modulus and Elasticity modulus), and devices placed in the drum of a roller, that are used to measure the response of soil during compaction. On the other hand, indirect measurement combines field measurement of water content and density, contrasted to a contour graph for response within the water-content-to-dry-density plane, referred to as RAMCODES "strength map", which is obtained through a laboratory factorial experiment described in the Venezuelan technical norm [15] for road construction (see Figure 2). The designer may define acceptance regions for all combinations of water content and dry density measured in the field that would meet any requested soil response, with the use of a strength map. The vulnerability at this level would certainly be lower than at Level 1 because the compacted soil response is measured and contrasted to the minimum request of the project. However, the major vulnerability at this level is that soil response is measured at the as-compacted hydration condition and in consequence, in soils susceptible to wetting, the soil response may notably differ (i.e., diminish, if the response is strength) from the measurement after compaction when the soil is wetted by rain, water vapor migration or any other source of suction loss. For instance, if soil compacted strength registers a value lower than that of project request caused by wetting, it could mean the failure of a backfill. Specifications written at Level 2 are ideal for clean soils, which are not susceptible to wetting. As a final note for this level, a minimum degree of compaction may be preestablished (by European Standard), or not (by Venezuelan Fondonorma norm), that is, it may be left to the designer to so choose because what really matters is performance, not density. This latter alternative is a considerable economical advantage in certain cases, as will be explained in the companion of this paper. Finally, a minimum value of degree of compaction is not a guaranty of quality unless it is related to the evaluation of performance of the soil being tested. Level 3 is called "conditioned performance". At this level the soil-material compliance specifications of Level 1 are also valid. However, it is also required that compacted soil exhibit the response required, under the particular hydration, surcharge and loading rate conditions of the project. By definition, the only way to achieve this is through the use of a design curve.

Therefore, the compacted soil at Level 3 is designed first, thereby obtaining a design curve; and only then, proceeding to establish the minimum compaction degree that can guarantee the achievement of required response and satisfy the project conditions at the same time.

Level 3 has two sublevels in regard to whether soil suction is controlled (sub-level 3a) or not (sub-level 3b) during laboratory testing.

At sub-level 3a, the soil suction is kept constant by means of a special triaxial test device array. In theory, there are at least four suction stress-state histories that can be emulated with the use of a constant-suction test device, namely: a) As-compacted state (i.e., zero suction change), b) Hydration path (i.e., suction loss), c) Dehydration path (i.e., suction gain), and d) Hydration-dehydration cycles. Suction-controlled devices are also the most reliable way to evaluate the effect of gradual hydration of compacted soil under soaking. Finally, sub-level 3a is by far the ideal environment to produce a reliable compacted soil design because the designer is able to measure the variation of soil's suction and correctly feed mathematical behavior models. Sub-level 3a constitutes an advanced stage of RAMCODES CSD method that will be discussed in a future paper.

At sub-level 3b, soil suction cannot be controlled, simply because testing devices employed do not have the capability. Testing devices as the classic triaxial chamber, or CBR, both in monotonic or cyclic loading, are examples of non-controlled suction devices. However, if soil specimens to be tested are elaborated under a factorial-experiment array of water content and compaction effort combinations, several design curves within a saturation degree range of interest may be obtained by means of a special graphics technique developed by the author which will be explained further in this paper. The sub-level 3b is an approximation to sub-level 3a for "as-compacted" suction stress-state history and constitutes the basic stage of RAMCODES CSD, to be fully explained in this paper. The vulnerability of design at Level 3 is the lowest of all because it is in full harmony with the definition of compacted soil design of the RAMCODES method. Sub-level 3a is superior to sub-level 3b because the former views suction as a state variable, and allows several suction stress-state histories to be considered. On the other hand, the latter views only the "as-compacted" suction stress history, in which suction is quantified indirectly by means of the degree of saturation of soil.

3.4. Designing at Sub-level 3b

The design at sub-level 3b requires a RAMCODES special technique consisting of three steps 1) to elaborate a laboratory factorial experiment, analyze its results and produce a contour graph called "strength map", 2) to produce a design curves spectrum, which is a group of design curves within the typical soil saturation degree ranging from 50 to 90 percent, and 3) to design the soil material, by establishing a minimum compaction degree value that assures that the compacted soil meets the required response under particular hydration, surcharge and loading rate conditions of the project. Many civil projects will also require the development of a design curve under total saturation conditions representing the worst hydration case. In general, there are mostly three common compacted soil responses used in civil projects, namely: strength (e.g., road backfills, structural backfills), permeability (e.g., impermeable cores of dams) and density (e.g., counter weight berms or shoulders). They can be used either individually or in certain combinations for specifying backfilling on civil projects. However, the most frequent response is strength. For that reason, as we proceed in this paper the strength response of the compacted soil will be our consideration, but allowing that permeability can be used instead. The author wants to make it perfectly clear that the response of density does not require the analyses contained in the following paragraphs. If any specification only requires the achievement of a certain density value, field test simply should be performed to verify that condition.

3.5. Factorial experiments and strength maps

A factorial experiment is a simple statistical design technique in which two or more independent factors are varied, within certain ranges of interest, in order to assess the influence of their interaction in the studied response. For the sake of convenience, RAMCODES uses compacted soil initial water content and dry density to formulate a two-factor factorial experiment to assess strength response while other factors such as the compaction method, confining pressure or surcharge, loading rate; are kept constant during the testing procedure. More than 12 years of experience in performing factorial experiments in a number of soil materials from gravels to clays would suggest that the minimum number of treatments (i.e., combinations of water content and density that produce a single soil specimen) is fifteen. For instance, in Proctor test (e.g., ASTM D 1557), compaction efforts of 12, 25 and 56 blows per layer are used. On the other hand, a number of five water content levels are employed and are referenced to optimum water content of the Proctor test. Every soil specimen is tested after compaction to obtain the strength parameter. After testing all specimens, there will be a matrix of at least fifteen rows composed of columns of water content (x-axis value), dry density (y-axis value), and the selected strength parameter (z-axis value). Any scientific software can produce a contour graph for strength within the water-content-versus-density plane, which is called in RAMCODES a strength map (see Figure 2).

3.6. RAMCODES special technique to plot design curves

The RAMCODES distinct technique for plotting design curves consists of intersecting a saturation degree curve, whose plot is obtained by means of the theoretical formula of saturation degree as a function of water content, dry density, and specific gravity of soil particles, with contour curves from the strength map. RAMCODES commonly uses the following saturation degree curves to perform the intersections of 50-, 60-, 65-, 70-, 80-, and 90 percent. The design curve for a saturation degree of 100 percent is obtained with results of specimens tested while saturated (triaxial test), or with 4-day soaked specimens tested under water (CBR test). Notice that to test specimens under water, it is necessary to deviate from the 15-minutes specimen pouring procedure of ASTM D 1883 because the compacted suction may be uncontrollably increased when such standard procedure is followed. All design curves obtained with this technique are then plotted in the same graph to produce a "design curves spectrum" (see Figure 3).

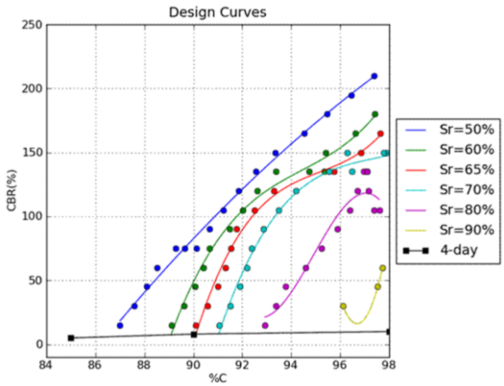

Figure 3. Strength map for CBR value.

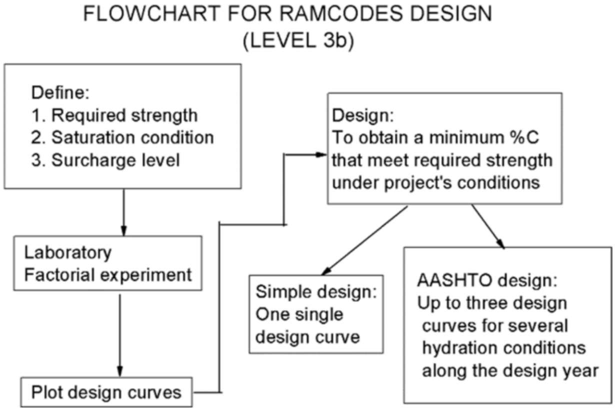

Figure 4. Flowchart for RAMCODES CSD design at Level 3b.

4. Compacted soil design

A compacted soil can be designed from a design curves spectrum by two methods, namely: a) simple design and, b) composed design. RAMCODES level 3b has the limitation that project specified hydration conditions are emulated using "as compacted" condition, because testing equipment used (v.g., CBR, triaxial) are not able to control hydration or dehydration paths. Simple design uses the design curve corresponding to the desired or the project specified saturation degree. This saturation degree is commonly established in project specifications as either the average or worst soil's service condition, based on a geotechnical or pavement study. The designer can choose between intersecting the design curve with pre-established compaction degree, and compare the obtained response to the project required response or, to the contrary, intersecting the design curve with the project required response, to obtain a compaction degree just high enough to meet the request. In the latter case, most designers use a minimum safety factor value, obtained as the ratio of the compacted soil response and the project required response, of 1.2 to verify the compacted soil design. Some pavement design methods (e.g.,AASHTO 1993, MEPDG 2002) use a weighted-average response (e.g., Elasticity modulus, resilient modulus, CBR) of the compacted soil that is obtained relating to three different hydration conditions, which are typically dry, wet and saturated conditions; and the number of months of a design year that the soil is correspondingly exposed to every hydration condition. Many countries draw-up and keep current their own climate maps that display the distribution of all hydration conditions. At RAMCODES level 3b, these hydration conditions can only be emulated using "as compacted" condition due to limitations of the laboratory equipment used. Figure 4 shows a flow chart to ease the comprehension and application of the RAMCODES CSD at Level 3b.

5. Applications

The paragraphs that follow are intended to show the application of RAMCODES CSD to actual civil engineering projects.

5.1. Proctor: Standard or Modify

The Modify Proctor (e.g., ASTM D 1557) is the most common used as a compaction reference for soils with fines and fine soils. In cases where limitations of space during construction, such as trenches and foundation backfilling, make it impossible to use heavy compaction equipment and as a result backfilling is performed with light-weight compactors, a typical practice is the use of Standard Proctor (e.g., ASTM D 668) instead of the Modify version, or to keep the Modify Proctor but reducing the compaction degree requirement (e.g., taking it 95- to 90-percent). However pragmatic, the practice of changing compaction reference only with respect to the compaction equipment, instead of the compacted soil's performance may produce a vulnerable backfilling, as will be proved in the following example with the use of design curves. The sub-base layer of a particular road is compacted with heavy rollers to the 95 percent of the Modify Proctor's maximum dry density, with the use of a soil that is in accord with its design curve, reaches CBR=20 percent of compaction degree and 80 percent of the saturation degree, which are both project's pavement design requirement values. A transversal trench is excavated, at a certain point of the road to place a sewer line after finishing the backfill. Once the pipe is then placed, the trench is backfilled to the surface of the road with the soil that was removed to open the trench. Light-weight compaction equipment is used because of space limitations ofthe trench. As a result of these circumstances, the engineers for the Inspector and the Contractor agreed to reduce the minimum degree of compaction from 95 to 90 percent of the Proctor MDD. Figure 5 would show that such decision is erroneous because, in accordance with the corresponding design curve, the CBR value of this soil at 90 percent of Proctor is roughly 5%. If the soil ever meets the design saturation degree, trench backfill will certainly collapse. This reasoning leads to the conclusion that, because of space limitations, the backfilling of a trench must be compacted with material of a better quality than that of the soil used in the embankment. In the example under discussion, such soil could be the silty gravel whose design curve is shown in Figure 6, in which this soil would exhibit a CBR value larger than 20 percent, at 80 percent of saturation, and at least 93 percent of compaction degree. This solution cannot be reached from Level 1 of the RAMCODES Pyramid.

5.2. Compaction, economy and security

Most engineers would promptly specify 95 percent of Proctor as the criterion for acceptance of compacted lots. Without doubt, this is a very strong and traditional paradigm that invariably relates to quality. However, the following two cases will show that, from Level 3 of the pyramid, the pre-establishment of a compaction degree—95 percent or whatever—without relating it to soil response, is an unacceptable practice. Figure 7 shows the design curve at 70 percent of degree of saturation for silty gravel with 65 percent of gravel content, to be used on a large embankment for tanks and machinery foundations. The project required strength is CBR=25 percent. As shown in the referred figure, that strength could easily be reached by compacting the soil at 92 percent of Proctor's MDD. However, if compacted at 95 percent of Proctor, this soil would exhibit a CBR value of 130 percent, that is, 2.6 times the project required strength. The amount of time and money that could be saved between 95 to 92 percent of compaction degree most times goes unappreciated. The results of a trial embankment for an oily project in eastern Venezuela indicate that an 8-ton roller compactor would need six passes to take a 25 cm layer of soil to a compaction degree of 95 percent while it would need only five passes to reach 92.5 percent of compaction. That difference of a single roller pass would represent 17 percent of savings in machine-operator time. A simple relation shows that this is a savings of 2 months per year. Also, [16] reported savings of 4 months per year during the construction of the embankments for railroads in central Venezuela, where the requested minimum CBR value was only 20 percent. Certainly, the savings related to time-machine in compaction is generally underestimated. Not only are the implications of this approach to economy important, but also to the security of the backfill structure, as will be shown in the following example. The use of a clayey gravel soil material is investigated as a pavement sub-base in which a minimum CBR value of 40 percent is requested, at 80 percent of saturation degree. The design curve at that hydration level is shown in Figure 8. Observe in that graph that a typical compaction degree of 95 percent of Proctor is not enough to comply with the referred strength request. In fact, the minimum compaction degree must be increased to 98 percent of Proctor; reason for which, the Contractor should weigh the economic implications of more compaction passes as opposed to the use and transport of a different soil material that would meet the required strength at a lower compaction degree.

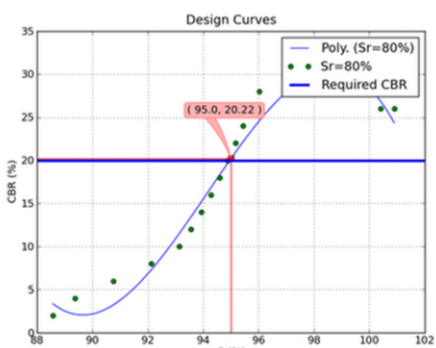

Figure 5. Design curve for a clayey sand used for trench backfilling. %C is the soil compaction degree.

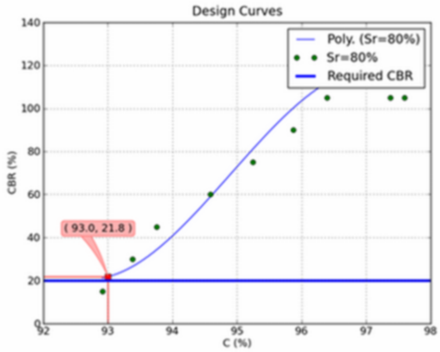

Figure 6. Design curve for a silty gravel at saturation degree of 80%. %C is the soil compaction degree.

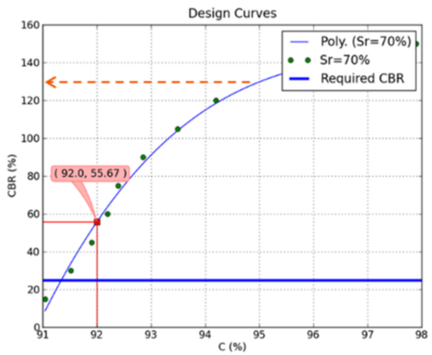

Figure 7. Design curve for a silty gravel, with 65% of gravel content, at saturation degree of 70%. %C is soil compaction degree.

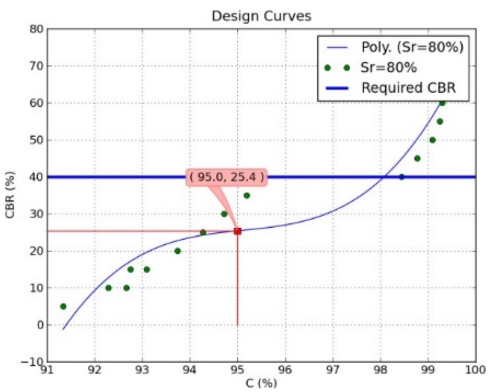

Figure 8. Design curve for a silty gravel at saturation degree of 80%. %C is the soil compaction degree.

5.3. Field validation with plate tests

Two 60-meter long and 2-meter high test embankments were built during the construction of a Venezuelan refinery in Puerto La Cruz, 550 km west from Caracas, to investigate field compaction equipment performance over a range of number of passes and layer thicknesses using a nuclear gauge to measure soil's density and water content. The investigation was also aimed to assess soil's Elasticity modulus, by performing several load plate tests of 65 cm diameter on the finished surfaces, to revise the bearing capacity of shallow foundations in the project [17]. These results were used to validate RAMCODES by comparison of laboratory design curves to field data. Laboratory design curves of embankment soil, a local silty gravel with 60 percent retained in sieve No. 4 and liquid limit of 25 percent, were elaborated for "as compacted" or unsoaked condition at several saturation degrees. In order to compare laboratory and field data, CBR test results were transformed into Elasticity modulus regarding the test as if it was a scaled plate test, using the same Boussinesq formula, shown below, as in [18] but using a diameter of 5 cm, which is the CBR piston diameter. Typical stress vs. settlement data for both load plate test and CBR test are presented in Figure 9.

$$E = \frac{\Delta\sigma}{\Delta\delta} B(1-\mu^2) I_p$$

where E: Elasticity modulus of soil, $\Delta\sigma$: pressure increment, $\Delta\delta$: settlement increment, B: diameter of the load plate (or piston), μ: Poisson's ratio and I_p: shape coefficient equal to 0.79 in circular plates.

In field, both soil's compaction degree and saturation degree were measured with a calibrated nuclear gauge. Figure 10 shows soil's design curves in terms of Elasticity modulus from CBR test (lines), and Elasticity modulus from load plate tests (dots). Observe that field data approaches to the design curve of 60 percent of saturation, which was the field average saturation degree measured by the nuclear gauge. According to this, laboratory design curves are comparable to field behavior which validates the RAMCODES design curves.

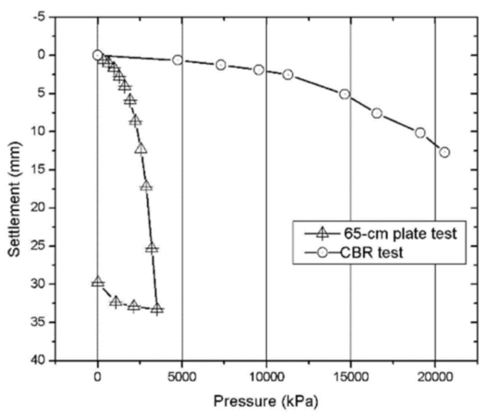

Figure 9. Typical stress vs. settlement curves for load plate test and CBR test.

5.4. Design curves of several soil types

The RAMCODES design curves are applicable to several soil types, as it is shown in Figure 11 in which the results of testing of a silty gravel from Puerto La Cruz (Venezuela), a clayey gravel from Boyacá (Colombia), a clayey sand from Puebla (Mexico), and a collapsible silty sand from Paraguaná (Venezuela), are presented. All design curves were elaborated for a saturation degree of 65 percent [17].

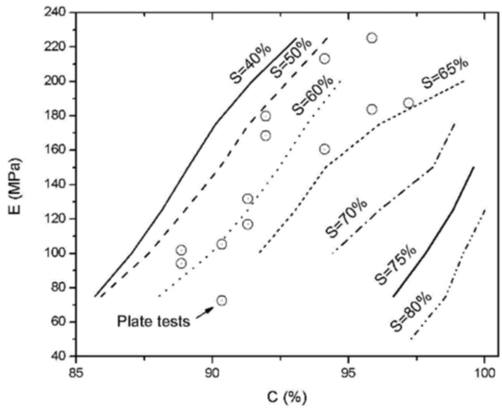

Figure 10. Comparison between laboratory design curves and field load plate test data.

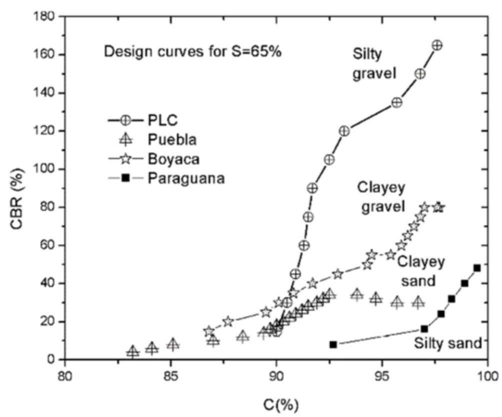

Figure 11. Design curves for several soil types at saturation degree of 65 percent.

6. Conclusions

The RAMCODES method for compacted soil design (CSD) has been introduced in this paper; and is supported by three main pillars: the design curve, the design pyramid and the QA/QC quadrants. The last of the pillars will be explained in a future work due to space limitations at this time.

For RAMCODES, designing a compacted soil is the determination of the minimum degree of compaction at which the soil exhibits a requested response under specific conditions of hydration, surcharge and loading rate.

A design curve is a plot that relates a soil compaction degree to its response under constant hydration, surcharge and loading rate conditions.

The RAMCODES design pyramid is a conceptual construction that introduces the different approaches or criteria for compacted soil design organizing them into a hierarchical order with respect to the vulnerability of design. Accordingly, there are two fundamental criteria for soil design, namely, compliance and performance; the first being the most vulnerable of all because it determines the quality of soil based on classification terms (v.g.,sieve analysis, plasticity of soil, soundness of soil coarse particles) but irrespective to performance verification; and the second being the compliance of a minimum degree of compaction that does verify the minimum performance required by project.

RAMCODES CSD uses a performance-based criterion to achieve a compacted soil design using several analyses techniques. This method allows the designer to design a soil by the simple method or by the composed method which produces a weighted average-strength value regarding several hydration conditions along the design-year.

This paper explains the use of the RAMCODES CSD method to design a compacted soil under a less vulnerable and most economical way by relating the civil project required response and hydration conditions.

This paper explains the use of the RAMCODES CSD method at Level 3b of the design pyramid in which project hydration conditions may only be emulated using "as compacted" condition due to the limitations of the equipment used (v.g., CBR, triaxial).

The design with RAMCODES at Level 3a, which is even less vulnerable than Level 3b, will be explained in a future work. At this level, the use of suction-controlled equipment may allow the emulation of more specific hydration paths, for instance, hydration defined as a loss of a fixed amount of suction from initial compaction condition.

The RAMCODES design curves are applicable to several soil types, projects and conditions, and results obtained in laboratory may be escalated so field conditions, as shown in this paper.

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