From Fundamentals to Applications in Compaction: Recent Developments in Embankments and Structural Layers of Pavements and Railways

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Portugal
Outline

- Background/ Historical
- Fundamentals
- Developments in Embankments
- Developments in structural layers
- Final remarks
Ralph R. Proctor, PE (1894-1962)

He started working at Los Angeles Bureau of Waterworks & Supply in 1916, integrated into the Department of Water & Power in 1931. He served in Co. E. of the 23rd Engineers in Europe during the First World War, constructing railroads. Returned to Los Angeles and rejoined the Department of Water & Power as a field engineer. He was the resident engineer for the St. Francis Dam during its construction (1924-26) and the post-failure surveys in 1928. He gained world renown for his work in developing the soil compaction test that bears his name in 1933, while working as resident engineer on the Bouquet Canyon dams (1932-34).

From 1933 until his retirement in 1959 he was in charge of design, construction, and maintenance of all dams in the LADWP system. He joined ASCE in 1927, becoming a Fellow and Life Member.

In 1948 Proctor authored four papers for the 2nd ICSMGE in Rotterdam, including one titled “The Elimination of Hydrostatic Uplift Pressures in New Earthfill Dams”, considered one of the pioneering papers on the subject.
Ralph R. Proctor, 4 articles in 1933

California Test 216 introduced by the California Division of Highways in 1929

Proctor (1933) - alternative method to California Test 216 - which allowed immediate adjustment of the soil water content, which was the critical variable the contractor needed to know.
Background/Historical

California Test 216 – Relative Compaction of Untreated and Treated Soils and Aggregates
Background/Historical

California Bearing Ratio – CBR
O. J. Porter (1927-30)

Test to evaluate the load bearing capacity of pavement subgrades and aggregate base courses, by comparing the penetration resistance of these materials with that of crushed limestone.
Background/Historical

Horse-drawn dirt bucket scrapper, California in 1885

Hopper dumping wagon, 1920
Side-dumping rail cars or wagons from temporary wooden trestles used in construction of large embankments

Sheepsfoot roller, Los Angeles in 1902
Background/Historical

1930s and 40s
Rapid development of mechanical compaction of soils

Highways work
Scotsman John L. McAdam
1756-1836

In 1816 published a book on road building that promoted a cambered 10-inch thick course of aggregate base rock, 16 feet wide. It employed a top course of < 2 inch rocks that each weighed less than 6 ounces, underlain by increasingly larger stones. These were then packed down by animals and wagon wheels.
Background/Historical

Five-ton limestone roller used to compact crushed limestone and river gravels in the China-Burma-India Theater during World War II, using the principles first advanced by John McAdam in 1816.
The “modified Proctor basis” of 1946 was developed by the US Army Corps of Engineers Waterways Experiment Station in Vicksburg.

It was designated ASTM Test D1557 or Modified AASHTO T180, initially adopted in 1958.

It was the first domestic airport runway designed using the new design methodologies, employing the Modified Proctor Compaction test on the aggregate basecourse.
ISSMGE 2nd Proctor Lecture

Background/Historical

ISSMGE – ETC 11 Main contributions

Past Publication of ETC 11

2000-05-19
Workshop during the INTERMAT 2000, Paris

• Modelling and compacted materials
• Compaction management and continuous control
ISSMGE 2\textsuperscript{nd} Proctor Lecture

Background/Historical

\textit{ISSMGE – ETC 11 Main contributions}

Past Publication of ETC 11

- 2001
- ETC 11 activities
- 1997-2001
Background/Historical

ISSMGE – TC 3 Main contributions

Past Publication of TC 3

(2005/09/14)
Workshop on: “Geotechnical aspects related to foundation layers of pavements and rail tracks”, organised during the 16th ICSMGE (Osaka), Japan

Roller-integrated continuous compaction control (CCC). Technical contractual provisions & recommendations, by D. Adam
ISSMGE – TC 3/202 Main contributions

ISSMGE - Webinar
Intelligent Compaction
Presenter: A. Gomes Correia and George Chang
Title: Intelligent Compaction
Date of recording: 25 November 2011
Duration: 01:44:14

The work of ISSMGE TC3 (Geotechnics of pavements) and how it links to earthworks
A. Gomes Correia, A. Quibel, M. Winter

Earth and rockfill embankments for road and railways: What was learned and where to go
A. Gomes Correia, H. Brandl, J-P. Magnan
Traveling Lecture Series: State of Good Repair

Intelligent Compaction: Standardization Needs from Manufactures to Users

A National University Transportation Center Consortium Event

By

A. Gomes Correia (agc@civil.uminho.pt)

University of Minho, Portugal & ISSMGE (TC202)
Compaction is applied to the soil to find optimum water content to maximise its dry density.

Aim: decrease soil’s compressibility, increase shearing strength, and in some cases, reduce permeability. => durability and stability of Earth structures.

Application: construction of roads, dams, landfills, airfields, foundations, hydraulic barriers, and ground improvements.
Fundamentals

Origin: Practical in dam’s construction: Proctor’s pioneering work, 1933

Theoretical approaches to explain phenomena (compaction curve):
- capillarity and lubrication (Proctor, 1933);
- viscous water (Hogentogler, 1936);
- theory in unsaturated soils: Hilf, 1956; Fredlund & Morgenstern’s (1976); Fredlund & Rahardjo (1993); Alonso et al. (1992); Gens (1995);
- physico-chemical interactions (Lambe, 1958, 1960);
- effective stress concept: Olson (1963); Fleureau et al. (1993); Alonso et al. (2010);

Support by microscopic observations:
- Barden & Sides (1970);
- Delage et al. (1996);
- Romero and Simms (2008)
Fundamentals

Microstructure and unsaturated approach
Alonso et al., 2010, 2013; Pinyol, 2016

A conceptual framework that incorporates microstructural information and accounts for the behaviour of compacted soils throughout the compaction plane.

Microstructure is quantified by a state variable = the ratio of microvoid ratio to total void ratio.

This state variable opens the way for a systematic evaluation of microstructural effects on measurable ‘macroscopic’ engineering variables, such as elastic stiffness, strength, compressibility, yielding behaviour and permeability.

Studies show that the microstructure of compacted clay-based soils are strongly dependent of the path to reach a point in the compacted curve.

Alonso, E. E. et al. (2013). Géotechnique 63, No. 6, 463–478
Development in Embankments

Important concepts for design

Earth structures (embankments) may be considered from two points of view:

- Structural design (Eurocodes 7, 8 or other rules e.g. for dams)

- Execution (How to build to obtain the needed properties. Standards of TC 396 Earthworks, ongoing)

In rail track serviceability limit state is very important because of the very restricted settlements – importance of geotechnical expertise – advanced construction technologies (materials, compaction, QC/QA)
Structural design checks the stability, deformations and hydraulic behaviour of the completed structure and its foundation. The mechanical and hydraulic properties assumed for design should be compatible with the material and construction procedures:

- deformability $E, E_{V2}, E_M$
- resistance for slope stability or bearing capacity $c', \varphi', q_c, p_{LM}$
- permeability (for dykes and dams, for liners in landfill sites) $k$

Structural design includes durability.
Developments in Embankments

Important concepts for design

Draft, Earthworks-Part 1: Principles and general matters

Part 1- Chapter 5 Earthwork design
5.3 Design of earthworks for embankments

Link $\rho_d$ and deformability, resistance, permeability

Embankments are divided into zones

Link $\rho_d$ and deformability, resistance, permeability.
**Developments in Embankments**

A unique $\rho_d/(\rho_d)_{max} \sim S_r - (S_{r_{opt}})$ relation

Nowadays we adopt a different acceptable zone, but we use the same approach, drawing isolines for suction, microstructure state variable, Engineering properties.

The proposed method encourages an increase in $\rho_d$ by using higher CEL while keeping $S_r = (S_r)_{opt}$.

1) Compaction curve by laboratory test (e.g., 1Ec)
2) $S_r = (S_r)_{opt}$
3) T: Compaction target
4) Compaction curve passing target point T (CEL$_T$ > 1Ec in this case)
5) DL
6) B
7) SL
8) WL passing point C
9) WU
10) SU
11) Acceptable zone for compacted backfill

Tatsuoka (2015);
Tatsuoka, Gomes Correia (2016)
Tatsuoka, Gomes Correia (2017)
In this area, $k$ may be too high while large collapse may take place upon wetting.

This area can be effectively eliminated by specifying an allowable lower bound for $S_r$ (e.g., 80%).
Compa action

Optimum thickness:
- Type of soil or rockfill;
- Maximum grain size;
- Water content during placing and compaction;
- Stiffness of the underlying layer;
- Compaction device and roller parameters;
- Compaction energy;
- Weather during compaction (e.g. frost);
- Quality requirements.

<table>
<thead>
<tr>
<th>Type of Compaction Plant</th>
<th>TC596 WG3 Material Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fine Graded Soil (wet state), Chalk</td>
</tr>
<tr>
<td>Smoothed wheeled roller (or vibratory roller operating without vibration)</td>
<td>✔</td>
</tr>
<tr>
<td>Grid Roller</td>
<td>✔</td>
</tr>
<tr>
<td>Deadweight tamping roller</td>
<td>✔</td>
</tr>
<tr>
<td>Pneumatic-tyred roller</td>
<td>✔</td>
</tr>
<tr>
<td>Vibratory tamping roller</td>
<td>✔</td>
</tr>
<tr>
<td>Vibratory roller</td>
<td>✔</td>
</tr>
<tr>
<td>Vibrating plate compactor</td>
<td>✔</td>
</tr>
</tbody>
</table>

Legend:
- ✔ Suitable
- ❓ Possibly suitable, depending on specific plant size and layer thickness
- ❌ Generally unsuitable
Developments in Embankments

Combination of the roller acceleration method and the roller positioning system (JGS-TC202, WG2)

Important contributions:
H. Brandl, D. Adam;
A. Quibel; A. Gomes Correia

TC3 (former TC202)
Roller-Integrated continuous compaction control (CCC):
Technical Contractual Provisions, Recommendations

ISSMGE Webinar on Intelligent Compaction (2 sessions), October 2011.
Gomes Correia, A. & Chang
Developments in Embankments

Modulus/Stiffness Devices (continuous monitoring tests)

On-board instrumentation and monitoring

100 % coverage of compacted area
Developments in Embankments

Demonstration Project (PT): Intelligent compaction technology for geomaterials

- IC roller BOMAG 213 DH-4 BVC: V4 (not taking into account IC technology);
- Conventional roller Caterpillar CS 683E: V5.

Gomes Correia and Parente, 2014
Method specification

**End product specification**: the designer specifies the degree of compaction necessary under a range of water content (degree of saturation) for the given material by reference to criteria linked to either serviceability or ultimate limit states.

**Performance specification**: the designer specifies in terms of the required serviceability limit state.

Modulus from CCC devices and moisture content (plus air voids) fit well with both specifications and can be monitored in real time.

Uniformity should be evaluated by the CV (15%, 15-20%)
ISSMGE 2nd Proctor Lecture

Developments in Embankments

Evaluation of accuracy and precision

Laboratory Small-Scale Tests

Moisture/Density Devices (spot tests)

• Soil Density Gauge (SDG)
  • electrical impedance spectroscopy (EIS)

• Speedy Moisture Tester (SMT)
  • Chemical reaction of wet soil with a calcium carbide reagent in a sealed pressure vessel.

• Time Domain Reflectometer (TDR)
  • dielectric permittivity
Developments in Embankments

- Soil Density Gauge (SDG)
- Speedy Moisture Tester (SMT)
- Time Domain Reflectometer (TDR)
- Nuclear Density Gauge
- Electrical Density Gauge
- DOT600

Moisture/Density Devices (spot tests)
Developments in Embankments *Modulus/Stiffness Devices (spot tests)*

- Geogauge
- Light Weight Deflectometer (LWD)
- Portable Seismic Property Analyzer (PSPA)
Analysis Results

Characteristics of Different Moisture Measurement Devices

<table>
<thead>
<tr>
<th>Device</th>
<th>Inaccuracy</th>
<th>Imprecision</th>
<th>Total Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDG</td>
<td>0.062</td>
<td>0.281</td>
<td>0.574</td>
</tr>
<tr>
<td>TDR</td>
<td>0.041</td>
<td>0.103</td>
<td>0.255</td>
</tr>
<tr>
<td>SMT</td>
<td>0.058</td>
<td>0.050</td>
<td>0.162</td>
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</tbody>
</table>

ANOVA Results of Moduli from Modulus-Based Device

<table>
<thead>
<tr>
<th>Measurement Device</th>
<th>Mean Modulus (MPa)</th>
<th>Repeatability (%)</th>
<th>Reproducibility (%)</th>
<th>Combined Device Variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zorn LWD</td>
<td>24</td>
<td>8</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Dynatest LWD</td>
<td>18</td>
<td>3</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>PSPA</td>
<td>154</td>
<td>14</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Geogauge</td>
<td>43</td>
<td>11</td>
<td>7</td>
<td>14</td>
</tr>
</tbody>
</table>
# Field trials – Full scale tests

## Évora, PT

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
</table>

## Objective: methodology of construction and quality control of railway embankments and rail track layers

Research Consortium UM/LNEC (FCT-UNL/IST)
Developments in Embankments

Field trials –
Full scale tests, Évora, PT

Clayey sand (SC)
- Void ratio $e=0.331$ (97% modified Proctor)
- Molding water content: $w_{OPM} - 4\% \mid w_{OPM} - 2\% \mid w_{OPM} \mid w_{OPM} + 2\%$
- Dry and saturated tests

Well-graded gravel (CA31.5)
- Void ratio $e=0.215$ (97% modified Proctor)
- Molding water content: $w_{OPM} - 2\% \mid w_{OPM}$
- Dry and saturated tests
Vibrating wheel:
- 1 meter diameter
- 0.20 meter width
- instrumented with accelerometers

Continuous determination of the stiffness at a constant speed of about 3.6 km/h.
• For this experiment it was seen correlation between SPLT and “Portancemètre” close to unit. These results validate the used calibration and testify huge potentiality of this equipment on the continuous stiffness evaluation on earthwork platforms.

• Correlation close to unit between SPLT and LWD, despite higher dispersion. This reveals too the practical utility of this kind of test easily manageable, although being a spot test.

• In relation to SSG (Geogauge) great dispersion was verified and EV modulus greater, approximately 40%, then EV2 modulus given by SPLT. Therefore, careful is required on equipment’s management and calibration.

• *These test results corroborate the small scale tests results*(Texas El Paso)

• *EN for Plate load tests and CCC – very important*
Comparison between full scale trial and laboratory results

Field trials – Full scale tests, Évora, PT

Research consortium UM/LNEC /FCT-UNL/IST
Developments in Embankments

Optimal approach to simulate proof-mapping using FEM - single- and two-layer geosystems

Models of linear vs. nonlinear material models, static vs. vibratory drums and stationary vs. moving rollers

Results are also used to obtain the depth of influence and the stress distribution beneath the drum

Relationships between the modulus of the base layer with the roller deflections recorded on top of the subgrade and base layers for linear systems (nonlinear in progress)

Validation of the results with several trials - MnROAD

IC can provide QC over 100% of compacted materials
Developments in Embankments

Create a synthesis of literature and manufacturer information that identifies methods used to compare IC measurements to soil mechanical properties, and the success of those methods.

Develop a criteria or procedure for field validating the relationship between IC measurements and soil mechanical properties.

Demonstrate the field calibration process using three different IC technology providers.

Illinois Tollway Research Project (2016-2018)

Project: Validation of Intelligent Compaction to Characterize Pavement Foundation Mechanical Properties

Coordinator (PI): Prof. Erol Tutumluer (Univ. of Illinois at Urbana-Champaign)
Data Mining (DM) is a process to extract high-level knowledge from raw data.

Different DM techniques: multiple regression, decision trees, k-nearest neighbors, neural networks, support vector machines, functional networks, etc.
Data Mining - Introduction

- In the past, several studies of Artificial Intelligence (AI) techniques on Geotechnics were used to determine prediction models for parameters considered by the finished product control.
- In this presentation, we deal with some AI applications, namely Data Mining (MR, SVM, ANN) for the design of soil improvement by jet grouting.


Data retrieved from GTR

Technology: Data Mining (DM)

- DM is applied to databases where results are known
- Can be used to predict the behaviour of new data in similar conditions/situations
- When applied to the GTR guide, it can very accurately estimate productivity of compaction equipment.

Predicted values vs. observed values for: Q/S parameter (left); e*V value (right)

Requirements for CCC rollers

Related instrumentation already available in other equipments for earthworks
Proposed system architecture

Results – algorithm convergence

Implementation of the system in a case study using real-world data from a Portuguese road construction site demonstrates its potential.

- Black line represents optimal solutions, grey points and lines represent initial and intermediate iterations, respectively.

Assessment of optimization algorithm convergence towards optimal solutions
Developments in structural layers

Soil stabilization

If technical issues are still the same...

1966

2006

Courtesy of Daniel Puiatti (Lhoist)
Developments in structural layers

Soil stabilization

... The technology has changed!

1966

Mixing

2006

Depth: down to 50cm

Courtesy of Daniel Puiatti (Lhoist)
Developments in structural layers

Soil stabilization

... The binders have changed

- Hydraulic Binders with lime
- Reduced dust lime
- Milk of lime
Developments in structural layers

Soil stabilization

Soils of laboratory studies

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil Type</th>
<th>Frequency</th>
<th>UCS</th>
<th>$E_0$</th>
<th>%Sand</th>
<th>%Silt</th>
<th>%Clay</th>
<th>%OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Lean clay (CL)</td>
<td>10</td>
<td>28</td>
<td>39.0</td>
<td>33.0</td>
<td>27.0</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Organic lean clay (OL)</td>
<td>5</td>
<td>18</td>
<td>6.0</td>
<td>57.0</td>
<td>37.0</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Fat clay (CH)</td>
<td>85</td>
<td>93</td>
<td>7.0</td>
<td>53.0</td>
<td>40.0</td>
<td>3.2</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Silty clay (CL-ML)</td>
<td>20</td>
<td>27</td>
<td>25.0</td>
<td>52.5</td>
<td>22.5</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>Lean clay (CL)</td>
<td>15</td>
<td>22</td>
<td>0.0</td>
<td>55.0</td>
<td>45.0</td>
<td>3.9</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Silty clay (CL-ML)</td>
<td>20</td>
<td>-</td>
<td>32.5</td>
<td>43.5</td>
<td>24.0</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>Lean clay (CL)</td>
<td>20</td>
<td>-</td>
<td>10.5</td>
<td>48.5</td>
<td>41.0</td>
<td>1.0</td>
<td></td>
</tr>
</tbody>
</table>
Developments in structural layers

Soil stabilization

UCS prediction based soft computing techniques

- ANN and SVM algorithms show a high performance in both UCS prediction of laboratory soil-cement mixtures ($R^2 \geq 0.97$);
- Both ANN and SVM present a very similar performance, which is significantly better than MR model.
Developments in structural layers

Soil stabilization

E₀ prediction based soft computing techniques

- Very high accuracy in E₀ prediction of laboratory soil-cement mixtures (R² ≥ 0.96), either by ANN or SVM algorithms.
Developments in structural layers

Soil stabilization

UCS and E₀ prediction – relative importance of parameters

- \( n/(C_{iv})^d \) is the key variable in both mechanical properties prediction of laboratory soil-cement mixtures.
- In UCS study the \( t \), \( C_{iv} \), and \( s \) also have a strong influence.
- Soil properties are apparently more relevant in stiffness prediction of laboratory soil-cement mixtures than in strength study.
**Developments in structural layers**

*Unbound Granular materials*

**x - Curve A (0/19)**
\[ E = 236 \frac{(2,10-e)^2}{(1+e)(\sigma/\text{pa})^{0.64}} \]
\[ R^2 = 0.85 \]

**+ - Curve B (0/6,35)**
\[ E = 167(2,15-e)^2/(1+e)(\sigma/\text{pa})^{0.67} \]
\[ R^2 = 0.80 \]

**0 - Curve C (0/2)**
\[ E = 127(2,17-e)^2/(1+e)(\sigma/\text{pa})^{0.63} \]
\[ R^2 = 0.98 \]
Developments in structural layers

*Unbound Granular materials*

Precision triaxial cyclic loading
(Local strain measurements – LDT)
- Curve A (0/19)
  \[ E/(\sigma/pa)^{0.64} = 106 \, e^{-1.33} \]
  \[ R^2 = 0.99 \]

+ - Curve B (0/6.35)
  \[ E/(\sigma/pa)^{0.67} = 91 \, e^{-1.38} \]
  \[ R^2 = 0.90 \]

o - Curve C (0/2)
  \[ E/(\sigma/pa)^{0.63} = 104 \, e^{-1.21} \]
  \[ R^2 = 0.98 \]
Developments in structural layers

Non traditional materials; importance of compaction parameters

Secant modulus and permanent strain with water content - “Vista Hermosa” material

Developments in structural layers

Non traditional materials; importance of compaction parameters

Developments in structural layers

Non traditional materials; importance of compaction parameters


(Taibi, 1994): \( g(s) = \sigma_u(s) \); derived from an elementary calculation based on Laplace law of a regular arrangement of spheres with the same diameter \( d \)
Developments in structural layers

Ballast stabilization methods

- Natural stabilisation ~ to cyclic vertical loads to the sleepers for a given time (dynamic uniaxial loading test on a sample).
- Dynamic stabilisation where the rails are vibrated laterally while applying a vertical load on them using dedicated equipment ~ biaxial loading test with varying confining pressure.
- Crib compaction - new in railway maintenance - direct vertical packing of the ballast located between the sleepers and in the shoulders of the track ~ compaction of a free surface granular medium.

Model: NSCD (LMGC90) code - DEM
Developments in structural layers

*Numerical Simulations: dynamic, crib compaction*

Dynamic stabilisation (grey) and crib compaction (black)

Lateral resistance as a function of sleeper displacement for inside sleepers (1, 2): for dynamic stabilisation (DYN) and crib compaction (CC)

Other studies using DEM related with ballast breakage and stabilisation: Indraratna team UoW; McDowell (UoNott); Cundall (1979)

Ferellec et al., 2017
(Sauussine team SNCF)
Final remarks

- **Compaction parameters** are key index properties influencing performance **based properties** and consequently **earth structures performance**

- Important to **integrate all chain of engineering design**: characterization – design – construction – performance/ durability

- Couple numerical modelling in laboratory and field analysis

- **IC** for earthworks and structural layers **can provide QC over 100% of compacted materials** and **link** performance based properties with **design**

- **Soft computing in Geotechnics** is an add tool to deal with **big data** (laboratory, field, monitoring) – retrieve existing data, predict and discover – **optimisation**, helping **decision making** (**JTC 2**)

- **DEM** in simulation of particulate materials – **ballast** – is powerful tool to help in many laboratory and field **parametric studies, solutions**, saving time and cost – helping **decision making**
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Thank you for your attention