ISSMGE 2nd Proctor Lecture

19th International Conference on Soil Mechanics and Geotechnical Engineering
17 (Sunday) ~ 22 (Friday) September 2017 COEX Convention Centre, Seoul, Korea

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

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Escola de Engenharia

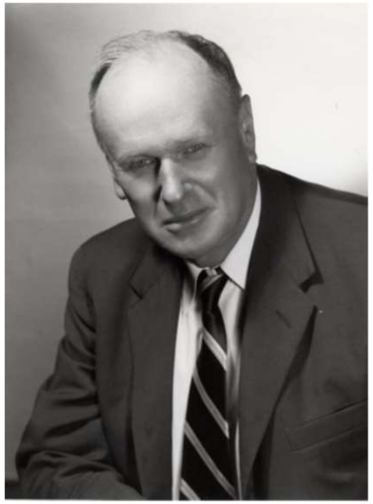
Institute for Sustainability and Innovation in Structural Engineering

Outline

- Background/ Historical
- Fundamentals
- Developments in Embankments
- Developments in structural layers
- Final remarks

Background/Historical

Ralph R. Proctor, PE (1894-1962)



He start 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.

Background/Historical

Ralph R. Proctor, 4 articles in 1933

Engineering
News-Record

Vol. 111 New York, August 31, 1933 No. 9

First of Four Articles on the Design and Construction of Rolled-Earth Dams

Fundamental Principles of Soil Compaction

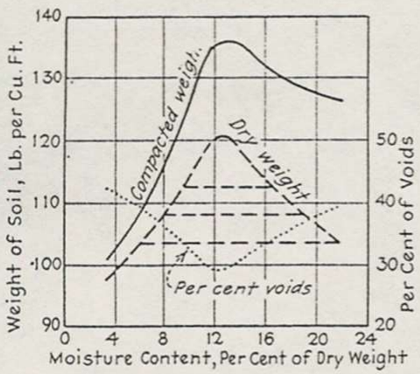
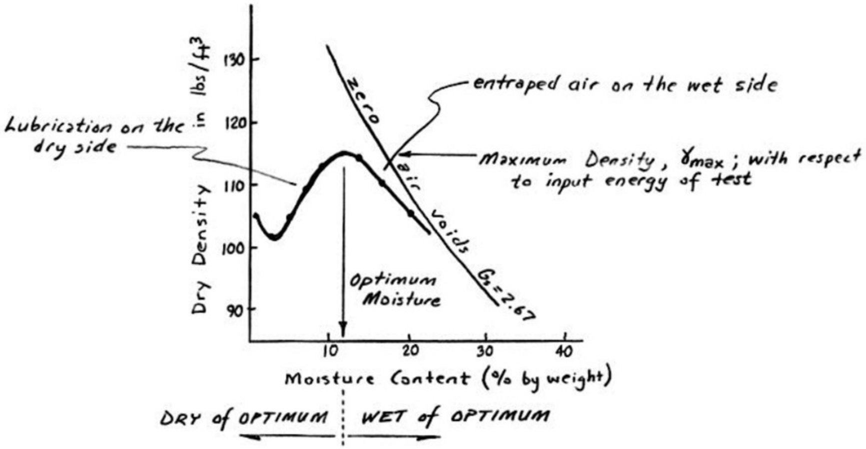


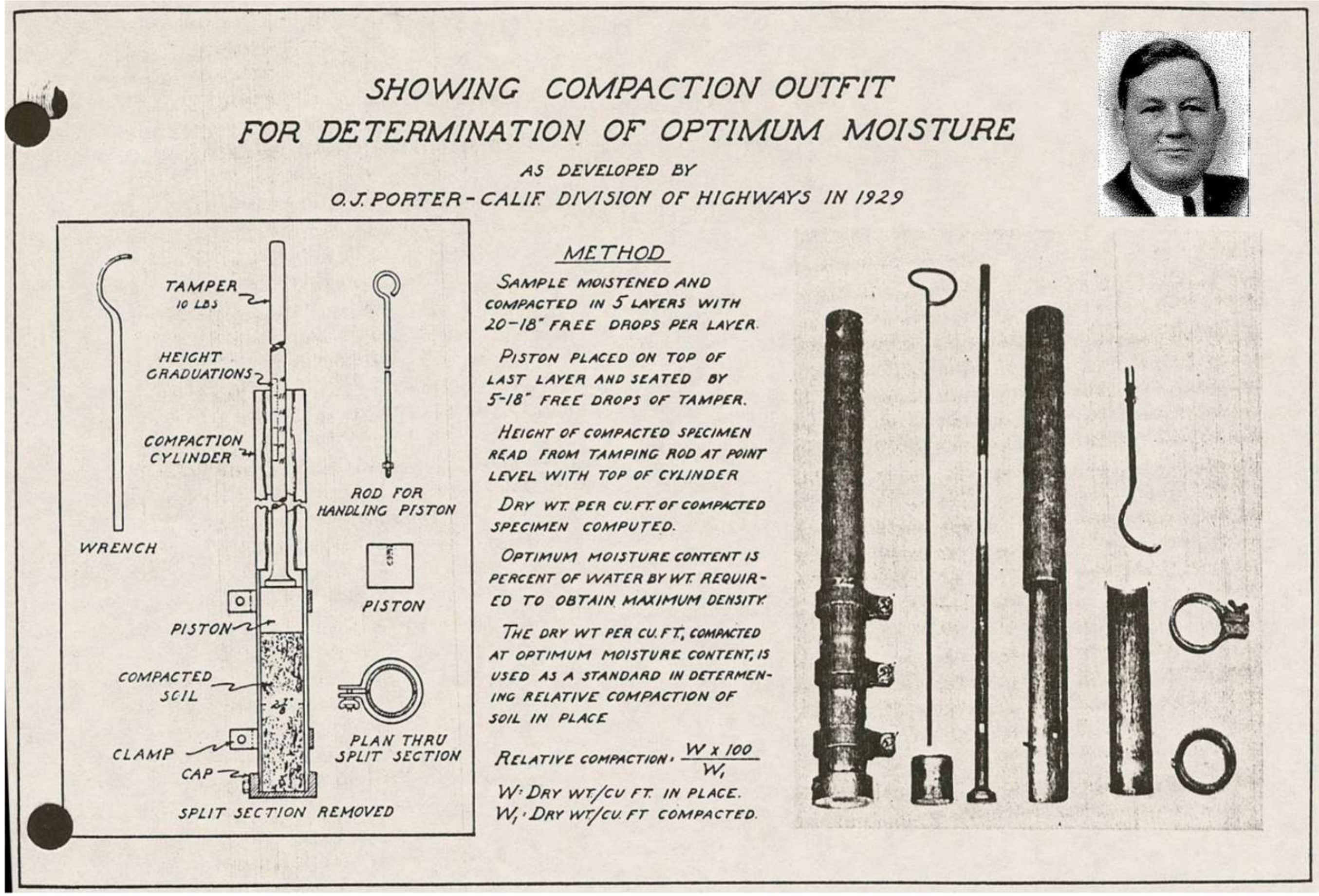
Fig. 2—Graph showing the effect of moisture content on the compacted weight, dry weight and voids of a soil when compacted by a particular method.

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



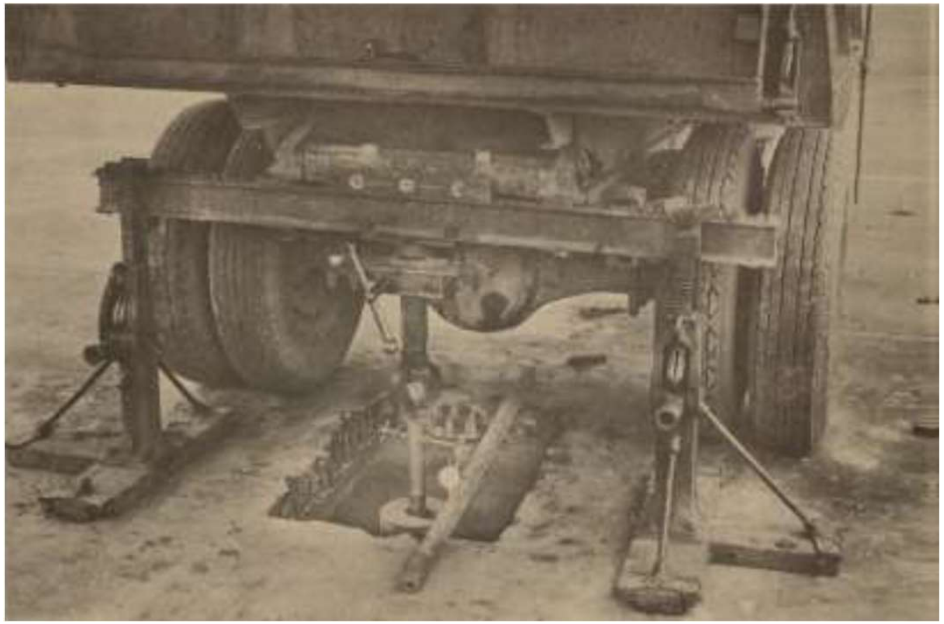
Proctor (1933) - alternative method to California Test 216 - which allowed immediate adjustment of the soil water content, which was the *critical variable* the contractor needed to know.

Background/Historical



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

Background/Historical

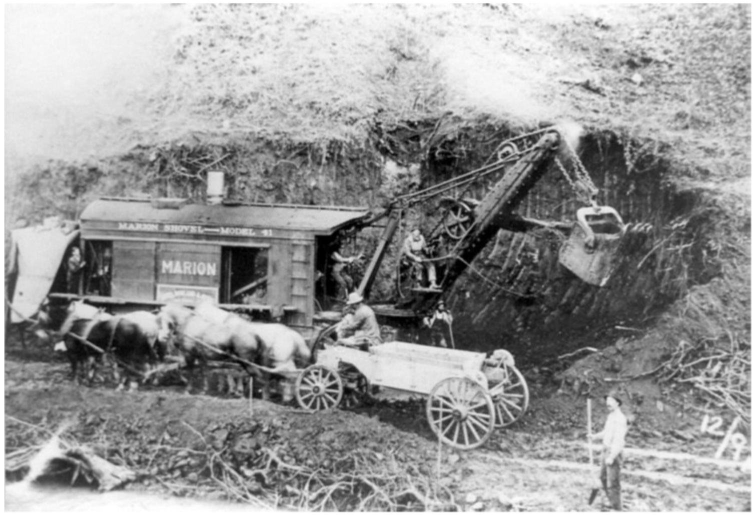


California Bearing Ratio – CBR
O. J. Porter (1927- 30)

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.

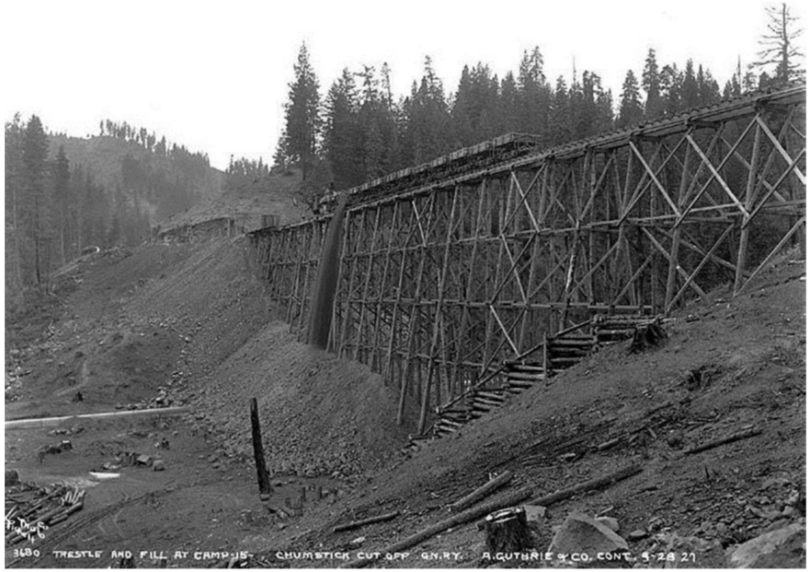
Background/Historical

Horse-drawn dirt bucket scrapper, California in 1885

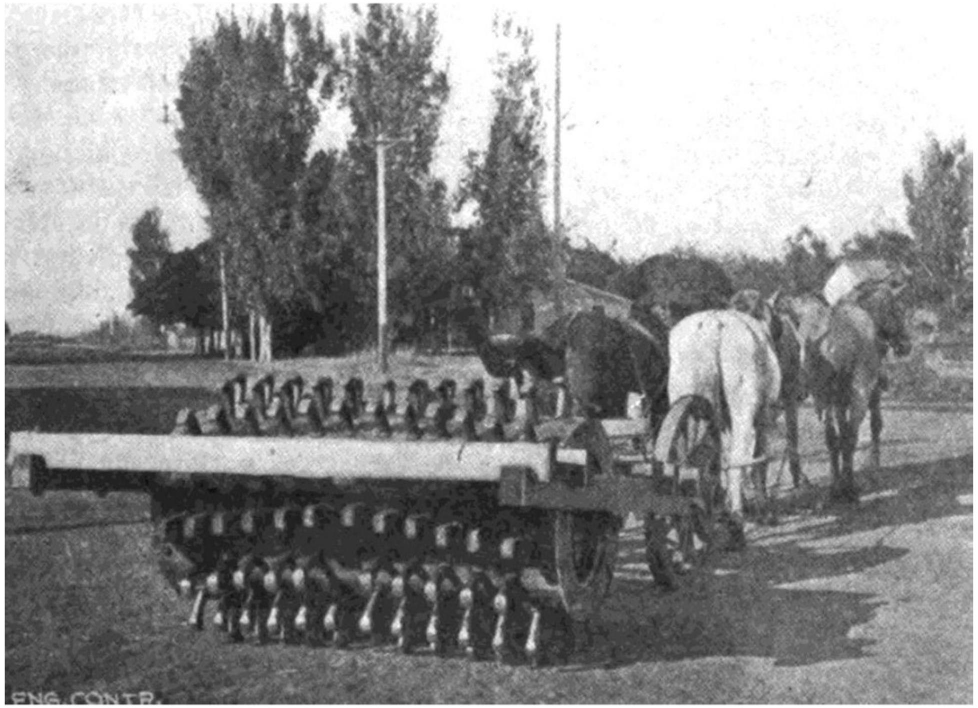


Hopper dumping wagon, 1920

Background/Historical



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



Sheepsfoot roller, Los Angeles in 1902

Background/Historical

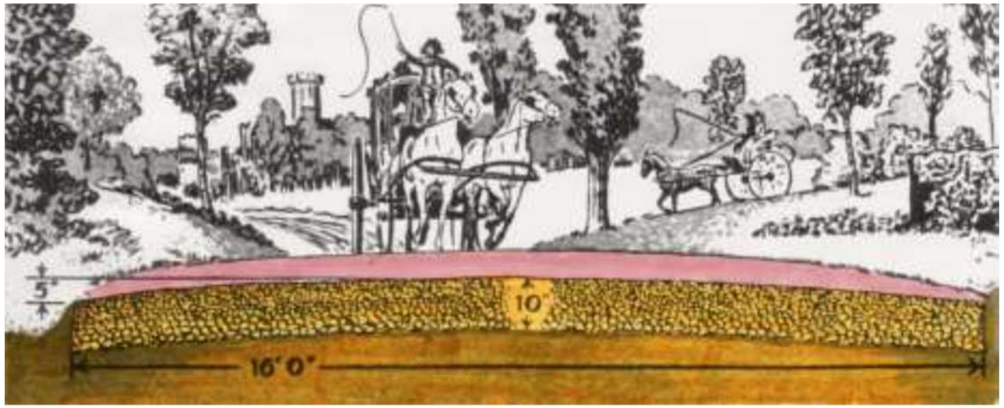
1930s and 40s
Rapid development of mechanical compaction of soils

Highways work

Background/Historical

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 of John McAdam in 1816

Background/Historical

O'Hare Airport (1947-62)

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

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***

Société Internationale de Mécanique des Sols et de Géotechnique

Comité ETC 11 - Aspects géotechniques dans la conception et la construction des chaussées et des voies ferrées

LE COMPACTAGE DES SOLS ET DES MATERIAUX GRANULAIRES

Propriétés des matériaux
Gestion du compactage et contrôle en continu

COMPACTION OF SOILS AND GRANULAR MATERIALS

Properties of compacted materials
Management of compaction and continuous control

PARIS - 19 Mai 2000

A. GOMES CORREIA
A. QUIBEL, éditeurs

«PUBLISHED BY PRESSES DE L'ECOLE DES PONTS ET CHAUSSÉS »

Background/Historical

ISSMGE – ETC 11 Main contributions

Past Publication of ETC 11

2001
ETC 11 activities
1997-2001

OUTCOME OF ETC 11 (EUROPEAN TECHNICAL COMMITTEE NO.11) OF ISSMGE
(INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING)

Geotechnics for Roads,
Rail Tracks and Earth Structures

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Vice-president of ISSMGE (1997-2001)

A.A.BALKEMA PUBLISHERS LISSE / ABINGDON / EXTON (PA) / TOKYO

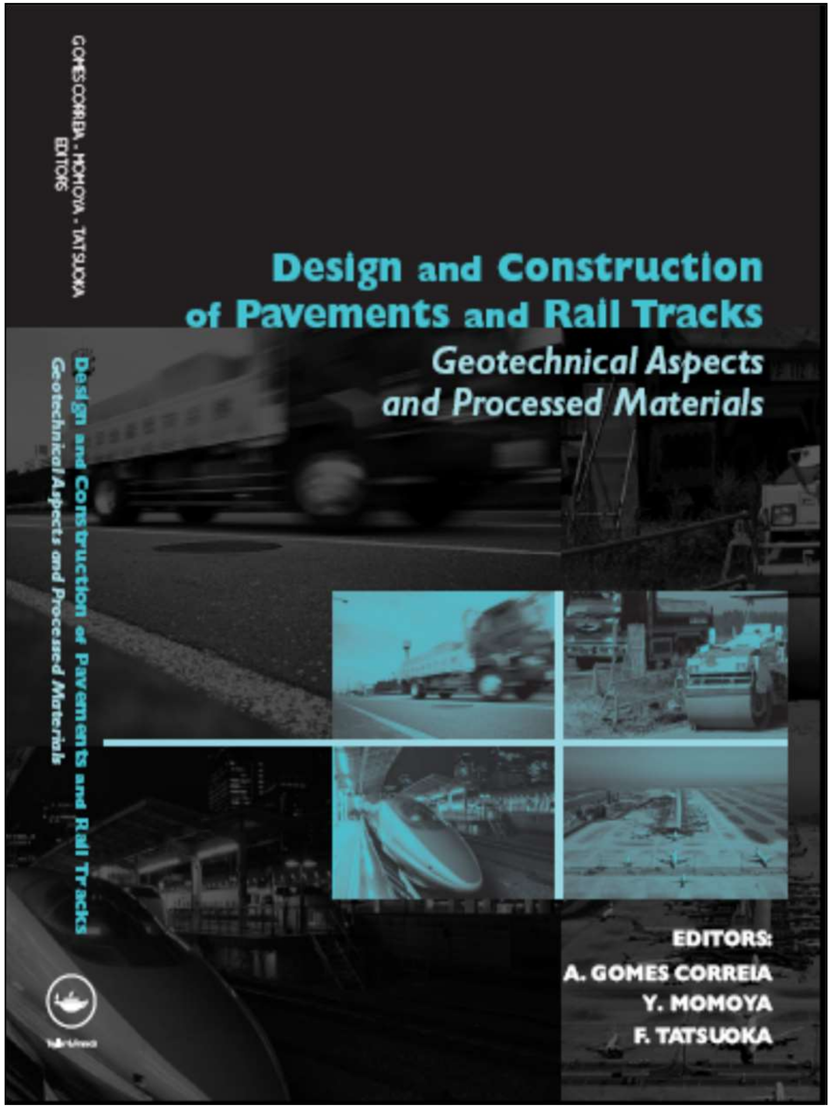
Background/Historical

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
http://www.issmge.org/en/resources/recorded-webinars/552-intelligent-compaction

The work of ISSMGE TC3 (Geotechnics of pavement s) and how it links to earthworks
A. Gomes Correia, A. Quibel, M. Winter
Geological Society, London, Engineering Geology Special Publications
2012, v.26; p67-77.

Earth and rockfill embankments for road and rail ways: What was learned and where to go
A. Gomes Correia, H. Brandl, J-P. Magnan
Keynote lecture at the XV Danube-European Conference
9-11 September 2014; 28pp.

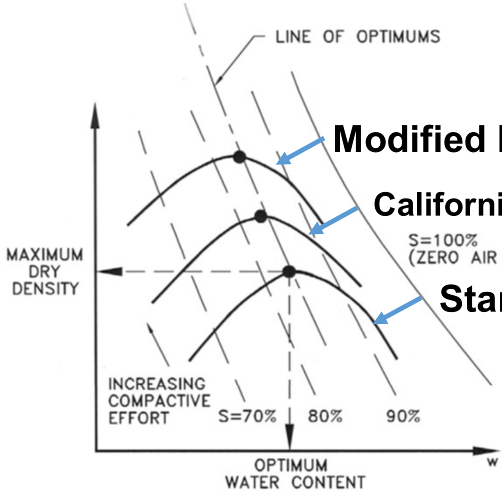
ISSMGE 2nd Proctor Lecture

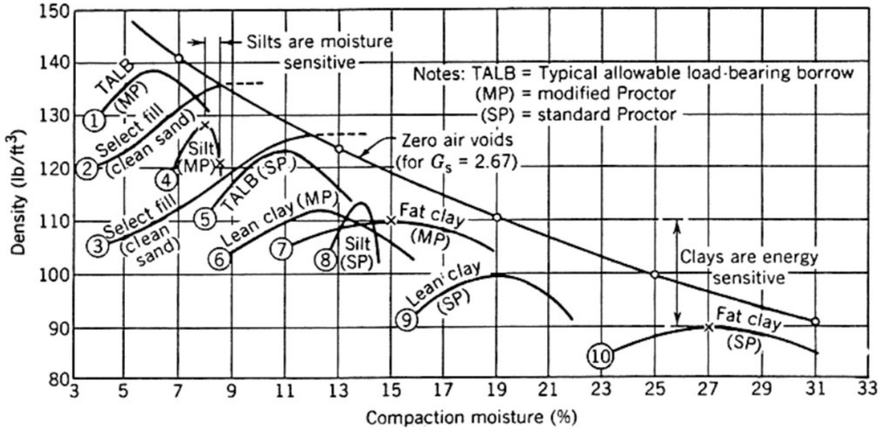
Fundamentals

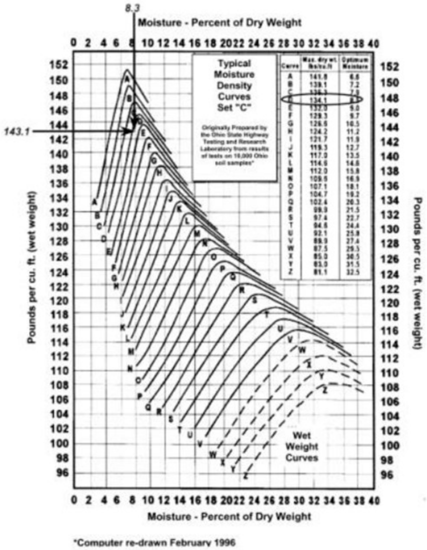
Compaction is applied to the soil to find optimum water content to maximise its dry density.

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.







Ohio DOT

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

Developments 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)

Developments in Embankments

Important concepts for design

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', φ', 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

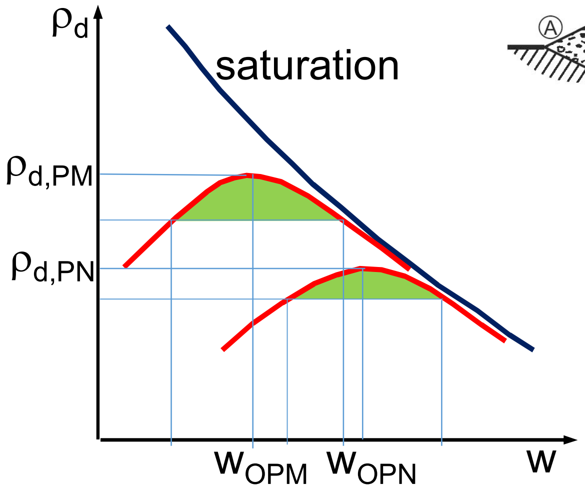
(Raoul & Magnan, Berlin 2012)

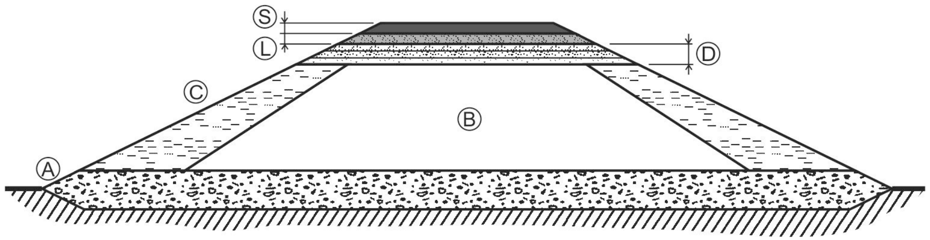
Draft, Earthworks-Part 1: Principles and general matters

Part 1- Chapter 5 Earthwork design

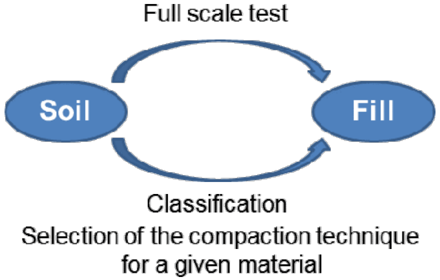
5.3 Design of earthworks for embankments

Link ρ_d and deformability, resistance, permeability



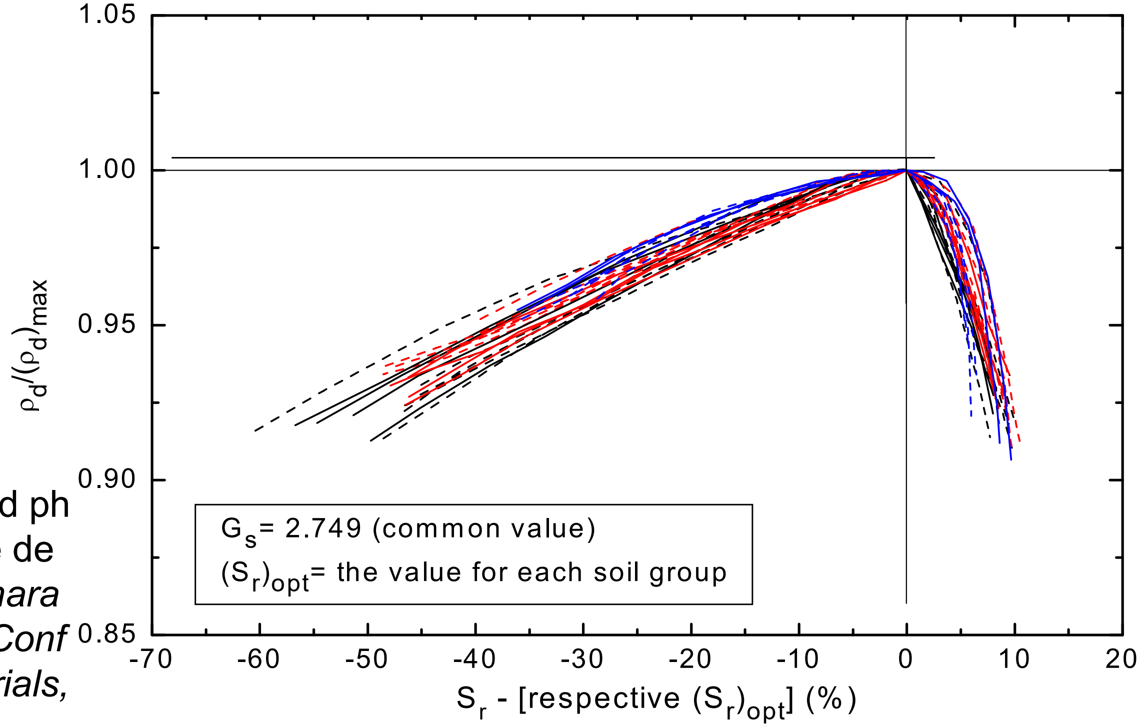


Embankments are divided into zones



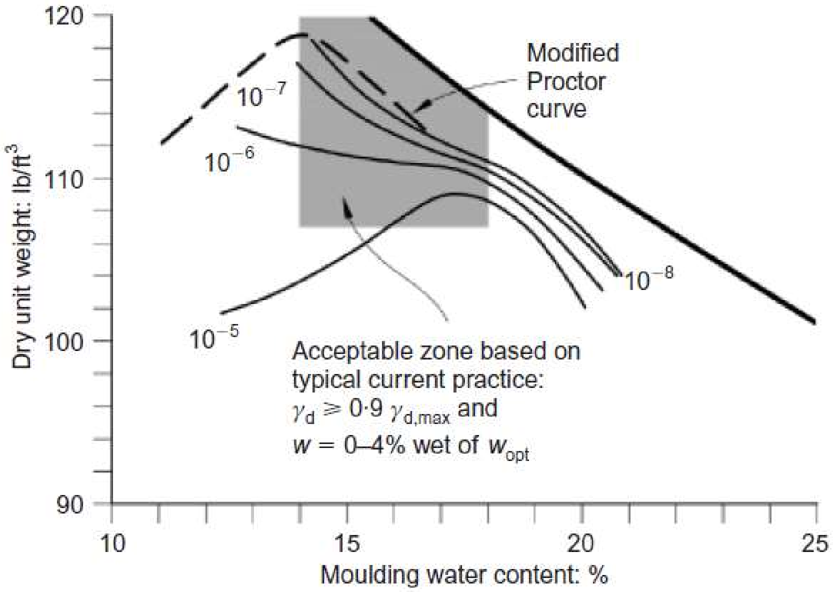
Developments in Embankments

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



Tatsuoka, F. (2015): Compaction characteristics and physical properties of compacted soil controlled by the degree of saturation, Keynote Lecture, *Deformation characteristics of geomaterials*, *Proc. of 6th International Conference on Deformation Characteristics of Geomaterials, Buenos Aires,* pp. 40-76.

Developments in Embankments

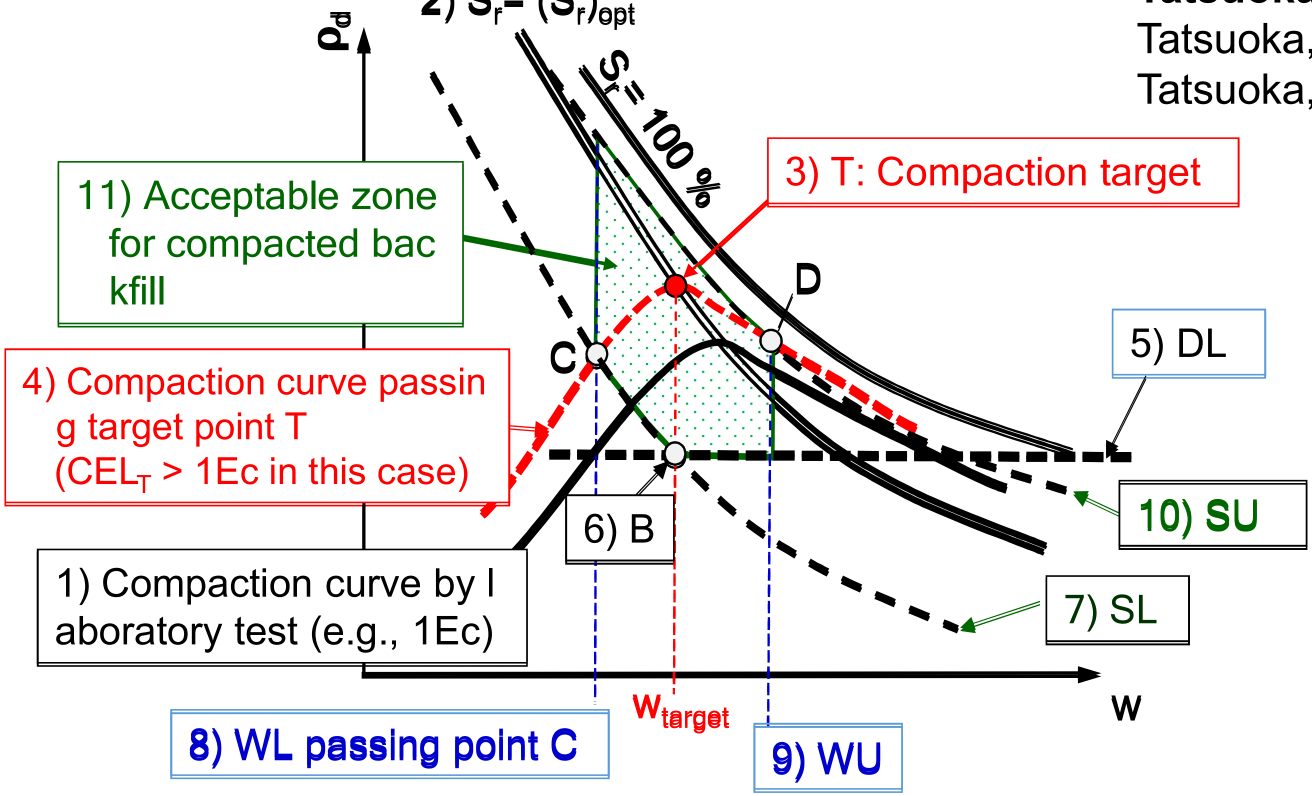


Mitchell, J. K., Hooper, D. R. & Campanella, R. G. (1965). Permeability of compacted clay. J. Soil Mech. Found. Engng Div. ASCE 91, No. 4, 4165

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

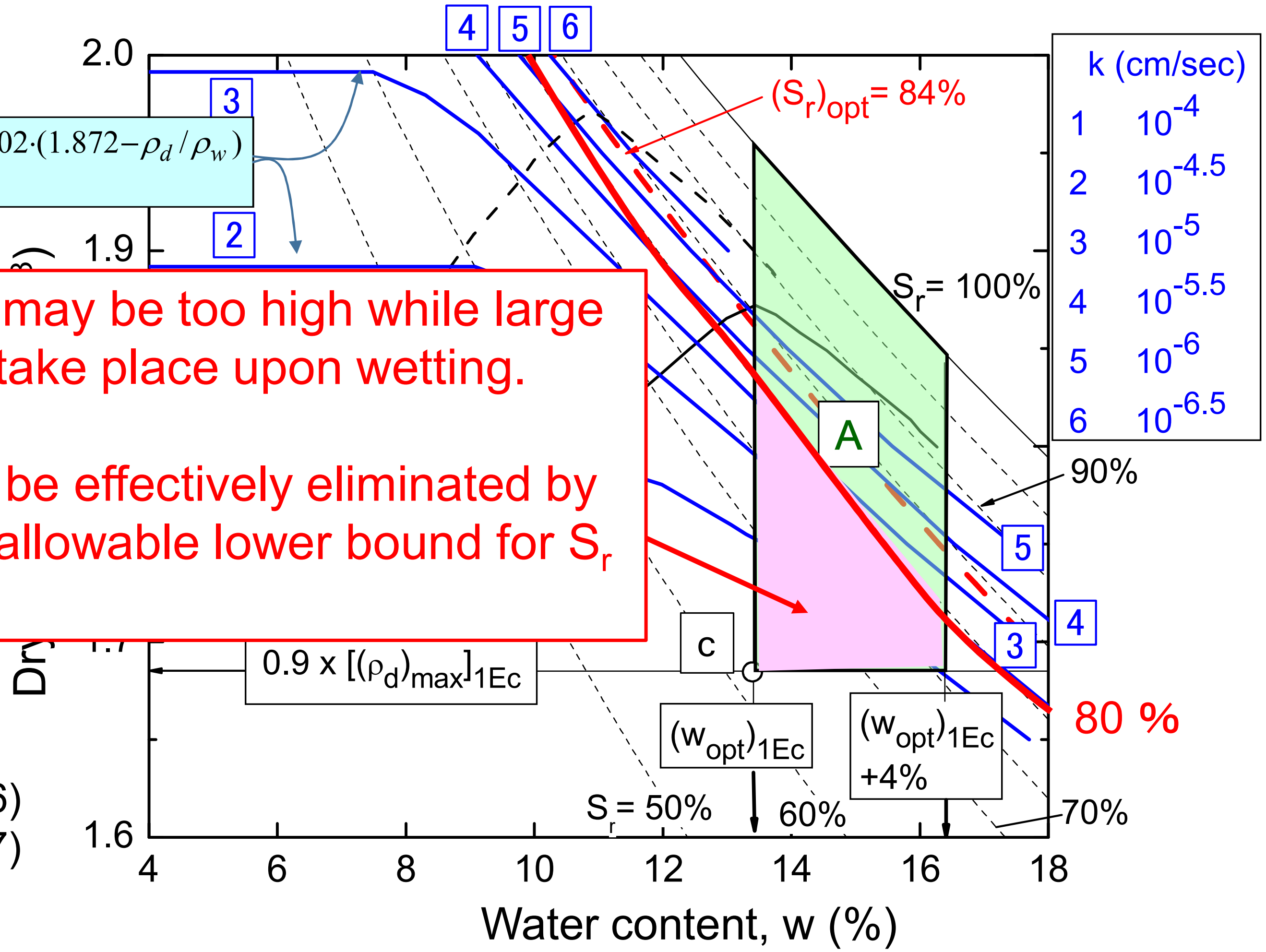
The proposed method encourages an increase in ρ_d by using higher CEL while keeping $S_r = (S_r)_{opt}$.

Tatsuoka (2015);
Tatsuoka, Gomes Correia (2016)
Tatsuoka, Gomes Correia (2017)



Contours of

$$k = f_k(S_r)\cdot 10^{5.02\cdot(1.872-\rho_d/\rho_w)}$$



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 %)

Tatsuoka (2015);
Tatsuoka, Gomes Correia (2016)
Tatsuoka, Gomes Correia (2017)

Developments in Embankments

Compaction

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.

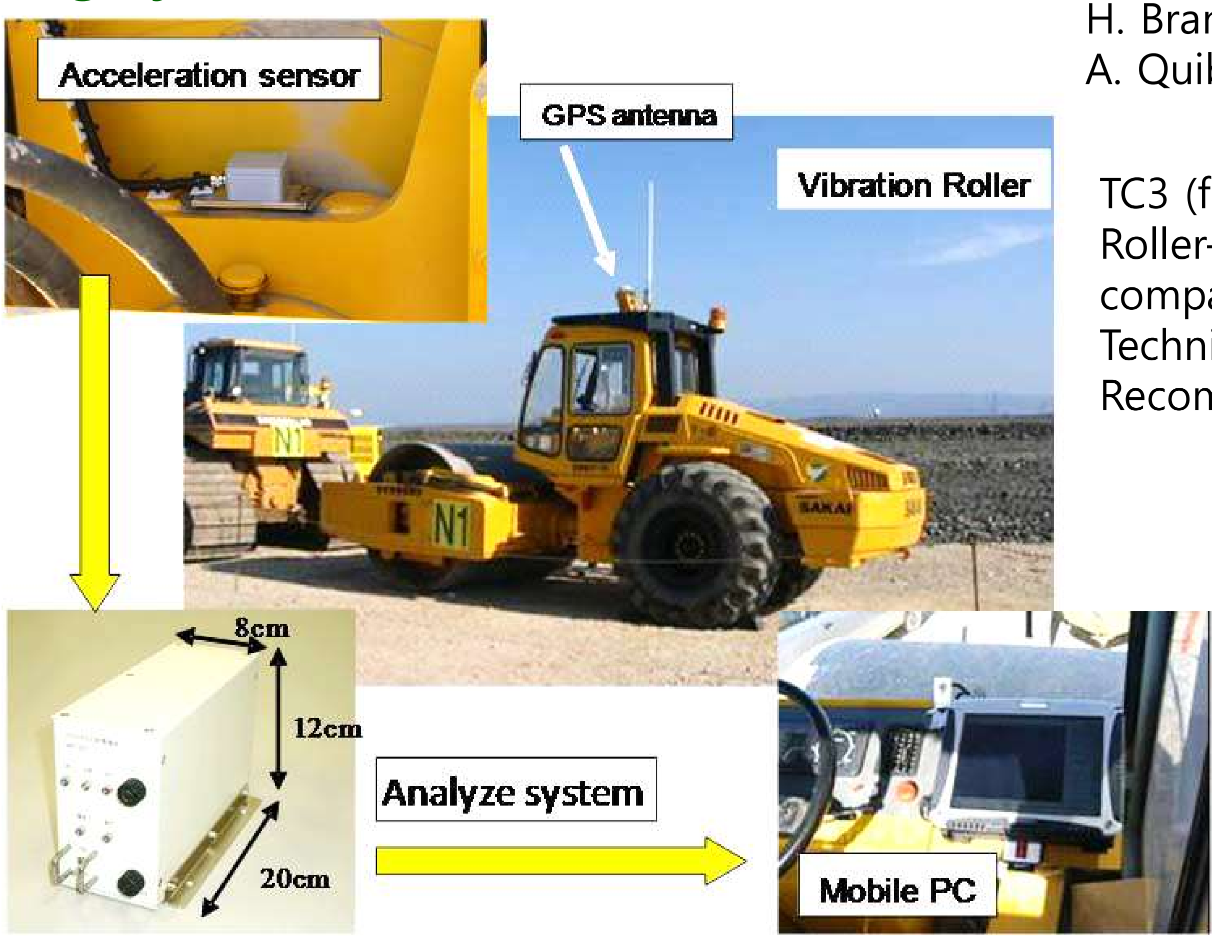
	TC396 WG3 Material Designation				
Type of Compaction Plant	Fine Graded Soil (wet state), Chalk	Fine Graded Soil (dry & normal state), Granular Soil (well graded)	Granular Soils	Weak Rock	Hard Rock
Smoothed wheeled roller (or vibratory roller operating without vibration)	Suitable	Possibly suitable	Possibly suitable	Suitable	Generally unsuitable
Grid Roller	Suitable	Possibly suitable	Generally unsuitable	Suitable	Generally unsuitable
Deadweight tamping roller	Suitable	Suitable	Generally unsuitable	Possibly suitable	Generally unsuitable
Pneumatic-tyred roller	Suitable	Suitable	Possibly suitable	Possibly suitable	Generally unsuitable
Vibratory tamping roller	Suitable	Suitable	Suitable	Possibly suitable	Possibly suitable
Vibratory roller	Suitable	Suitable	Suitable	Suitable	Suitable
Vibrating plate compactor	Possibly suitable	Suitable	Suitable	Possibly suitable	Possibly suitable

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



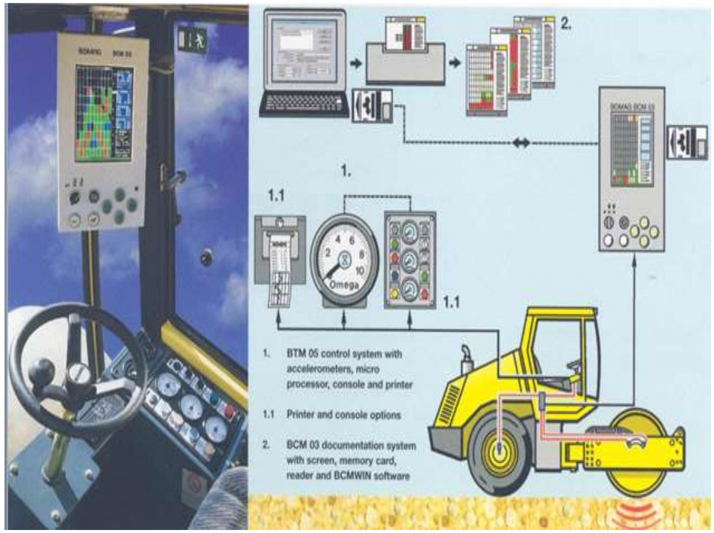
TC3 (former TC202)
Roller-Integrated continuous compaction control (CCC): Technical Contractual Provisions, Recommendations

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

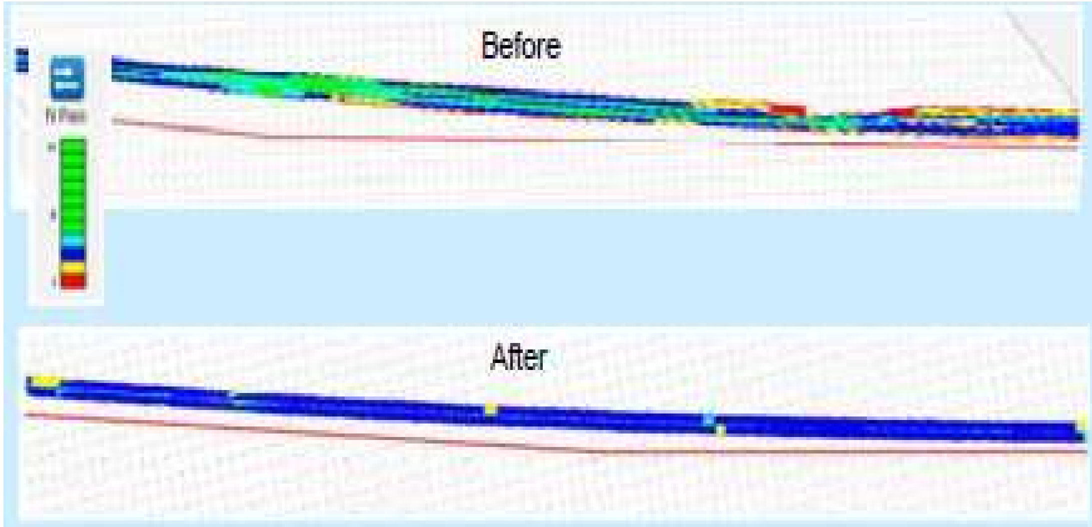
Developments in Embankments

Modulus/Stiffness Devices (continuous monitoring tests)

On-board instrumentation and monitoring



CEN/TS 17006:2016 Earthworks - CCC



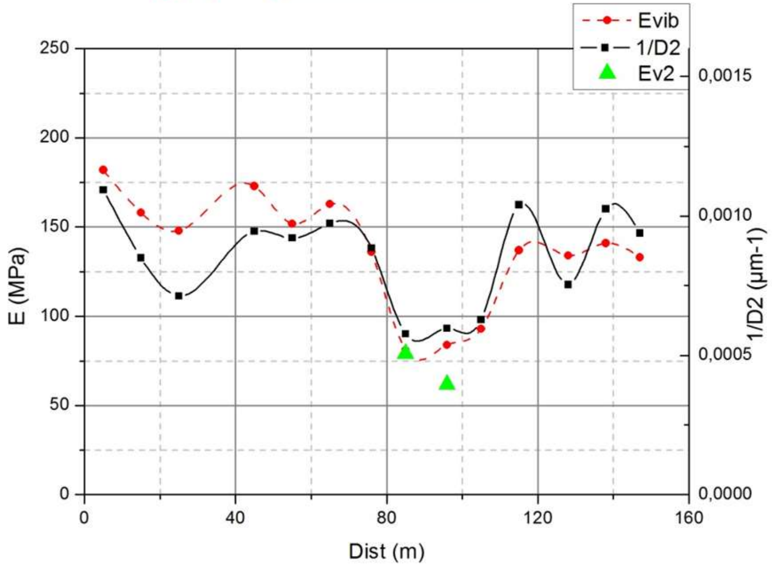
100 % coverage of compacted area

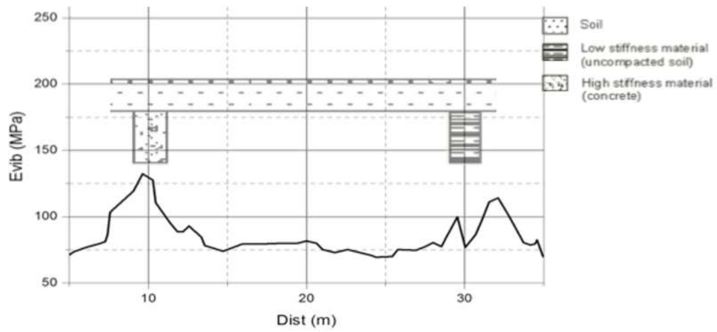
Developments in Embankments

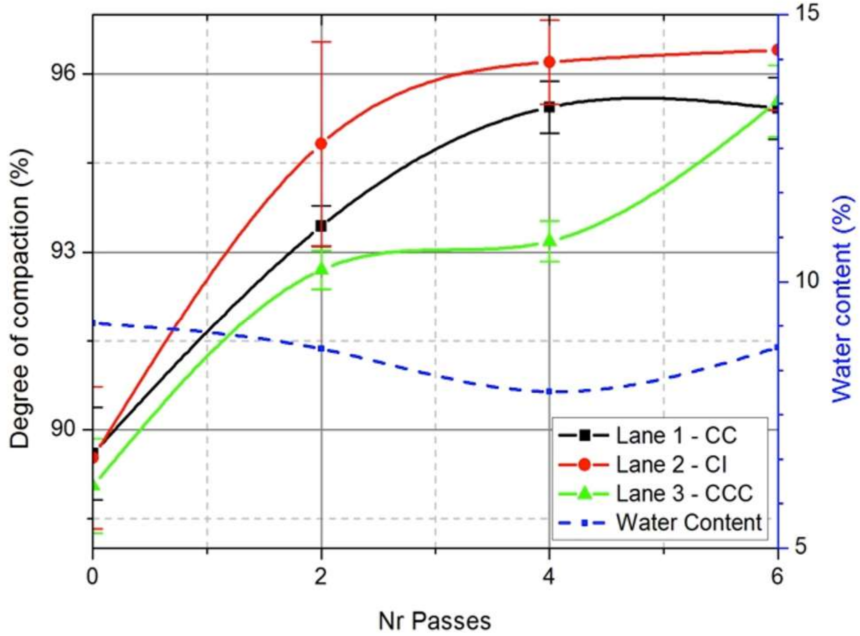
Demonstration Project (PT): Intelligent compaction technology for geomaterials

Gomes Correia and Parente, 2014

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







Developments in Embankments

Design - Method of compaction

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%)

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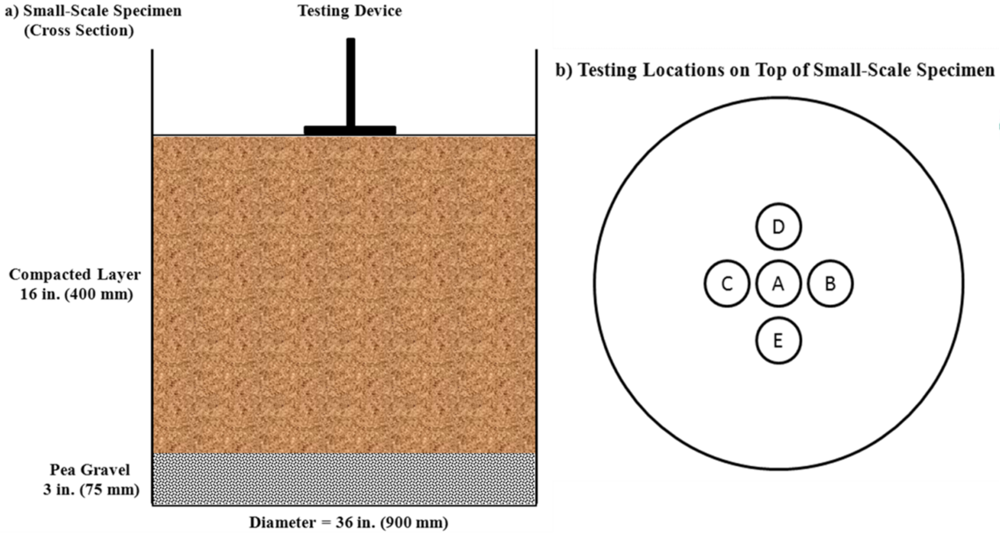
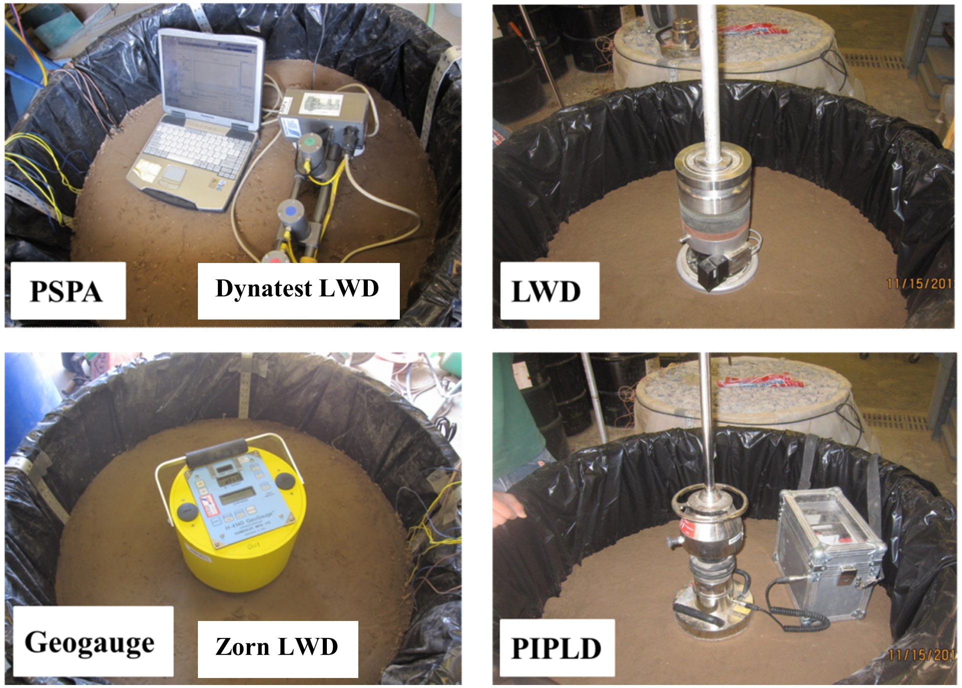
Developments in Embankments

Evaluation of accuracy and precision

Laboratory Small-Scale Tests

Gomes Correia, A.; Nazarian, S. Construction and Quality Control of Railway Embankments and Compacted Layers, International Journal of Railway Technology, 3(1), 63-81, 2014. doi: 10.4203/ijrt.3.1.3





Developments in Embankments

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

Moisture/Density Devices (spot tests)

- Soil Density Gauge (SDG)

- Speedy Moisture Tester (SMT)

- Time Domain Reflectometer (TDR)

- Nuclear Density Gauge

- Electrical Density Gauge

- DOT600

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

- Geogauge

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

Developments in Embankments

Analysis Results

Characteristics of Different Moisture Measurement Devices

Device	Inaccuracy	Imprecision	Total Error
SDG	0.062	0.281	0.574
TDR	0.041	0.103	0.255
SMT	0.058	0.050	0.162

ANOVA Results of Moduli from Modulus-Based Device s

Measurement Device	Mean Modulus (MPa)	Repeatability (%)	Reproducibility (%)	Combined Device Variation (%)
Zorn LWD	24	8	7	10
Dynatest LWD	18	3	13	13
PSPA	154	14	5	15
Geogauge	43	11	7	14

19th International Conference on Soil Mechanics and Geotechnical Engineering
Seoul 2017 19th ICSMGE
17 (Sunday) ~ 22 (Friday) September 2017 COEX Convention Centre, Seoul, Korea

Developments in Embankments

Research Consortium UM/LNEC /FCT-UNL/IST)

		1	2	3	4	5	6	7	8	9	10	
A	LA	SRM-WC-SPLT-LFWD-SSG (4)		SRM-WC-SPLT-LFWD-SSG (6)		SRM-WC-SPLT-LFWD-SSG (8)		SRM-WC-SPLT-LFWD-SSG (6)	SRM-WC-SPLT-LFWD-SSG (8)		SRM-WC-SPLT-LFWD-SSG (4)	PORTANCE MÉTRE
			SRM-WC-SPLT-LFWD-SSG (10)		SRM-WC-SPLT-LFWD-SSG (12)		SRM-WC-SPLT-LFWD-SSG (12)			SRM-WC-SPLT-LFWD-SSG (10)		
B	L1											PORTANCE MÉTRE
		WC-LFWD-SSG						WC-LFWD-SSG				
	L2											
					WC-LFWD-SSG						WC-LFWD-SSG	
	L3											
C	LC	SRM-WC-SPLT-LFWD-SSG (6)	SRM-WC-SPLT-LFWD-SSG (8)	SRM-WC-SPLT-LFWD-SSG (4)				SRM-WC-SPLT-LFWD-SSG (4)		SRM-WC-SPLT-LFWD-SSG (8)	SRM-WC-SPLT-LFWD-SSG (6)	PORTANCE MÉTRE
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Field trials –
Full scale tests
Évora, PT

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

Developments in Embankments

Research consortium UM/LNEC /FCT-UNL/IST)

Field trials – Full scale tests, Évora, PT

Clayey sand (*SC*)

- Void ratio e=0.331 (97% modified Proctor)
- Molding water content: w_{OPM}-4% | w_{OPM}-2% | w_{OPM} | w_{OPM}+2%
- Dry and saturated tests

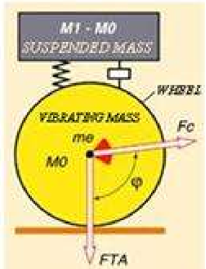
Well-graded gravel (*CA31.5*)

- Void ratio e=0.215 (97% modified Proctor)
- Molding water content: w_{OPM}-2% | w_{OPM}
- Dry and saturated tests

Developments in Embankments

Modulus/Stiffness Devices (continuous monitoring tests)

"Portancemètre"



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.

Developments in Embankments

Research consortium UM/LNEC /FCT-UNL/IST)

Analysis Results — *Field trials – Full scale tests, Évora, PT*

- 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)***

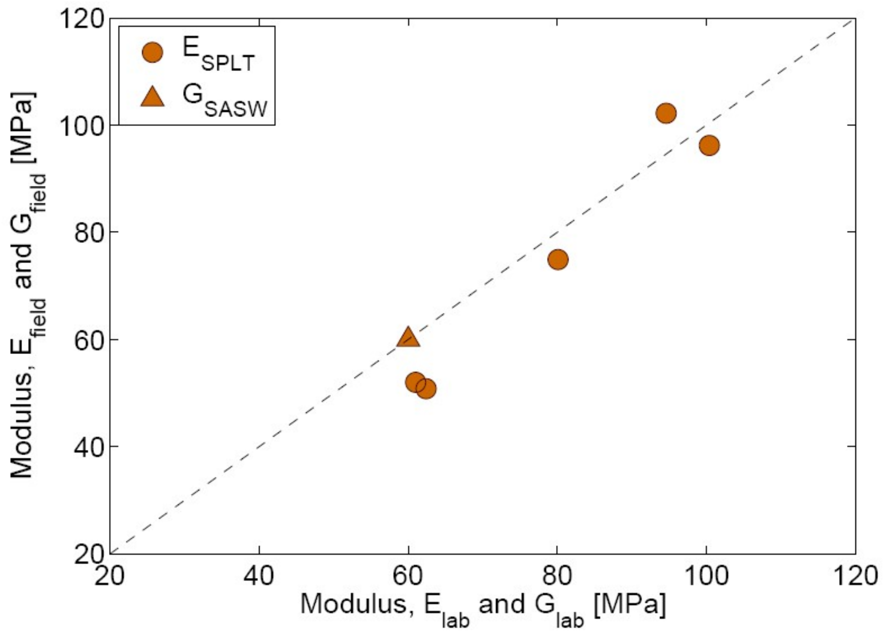
- ***EN for Plate load tests and CCC – very important***

Developments in Embankments

Research consortium UM/LNEC /FCT-UNL/IST)

Field trials –
Full scale tests, Évora, PT

Comparison between full scale trial and laboratory results



Developments in Embankments

National Cooperative Highway Research Program (NCHRP)

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

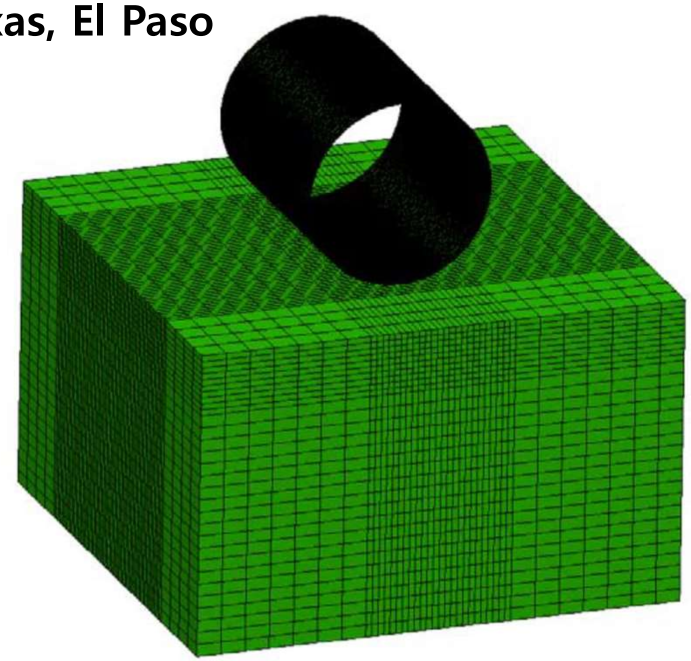
Relationships between the modulus of the base layer with the roller deflections recorded on top of the subgrade and base layers for linear systems (nonlinear in progress)

Validation of the results with several trials - MnROAD

IC can provide QC over 100% of compacted materials

Project: Evaluating Mechanical Properties of Earth Material during Intelligent Compaction

Coordinator (PI): Prof. Soheil Nazarian, U. Texas, El Paso



Developments in Embankments

Illinois Tollway Research Project (2016-2018)

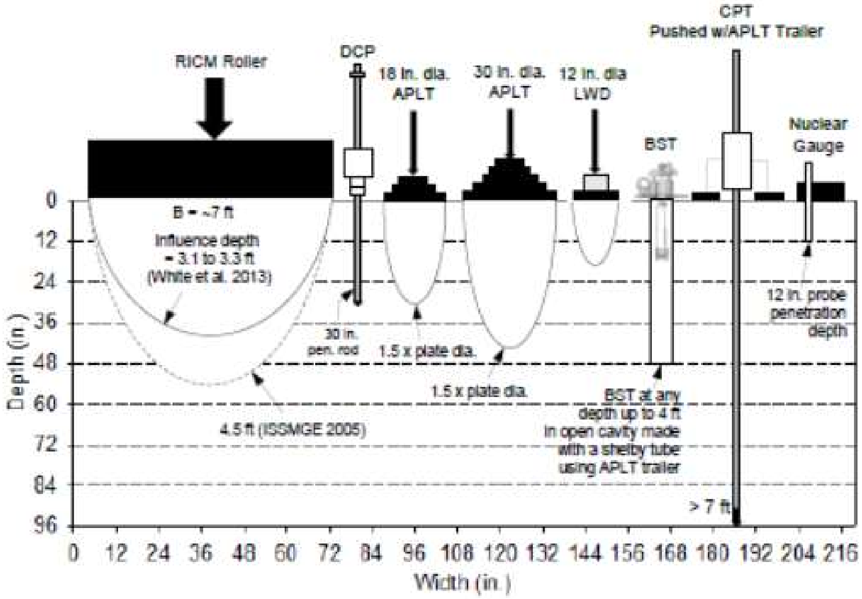
Create a synthesis of literature and manufacturer information that identifies methods used to compare IC measurements to soil mechanical properties, and the success of those methods

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

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

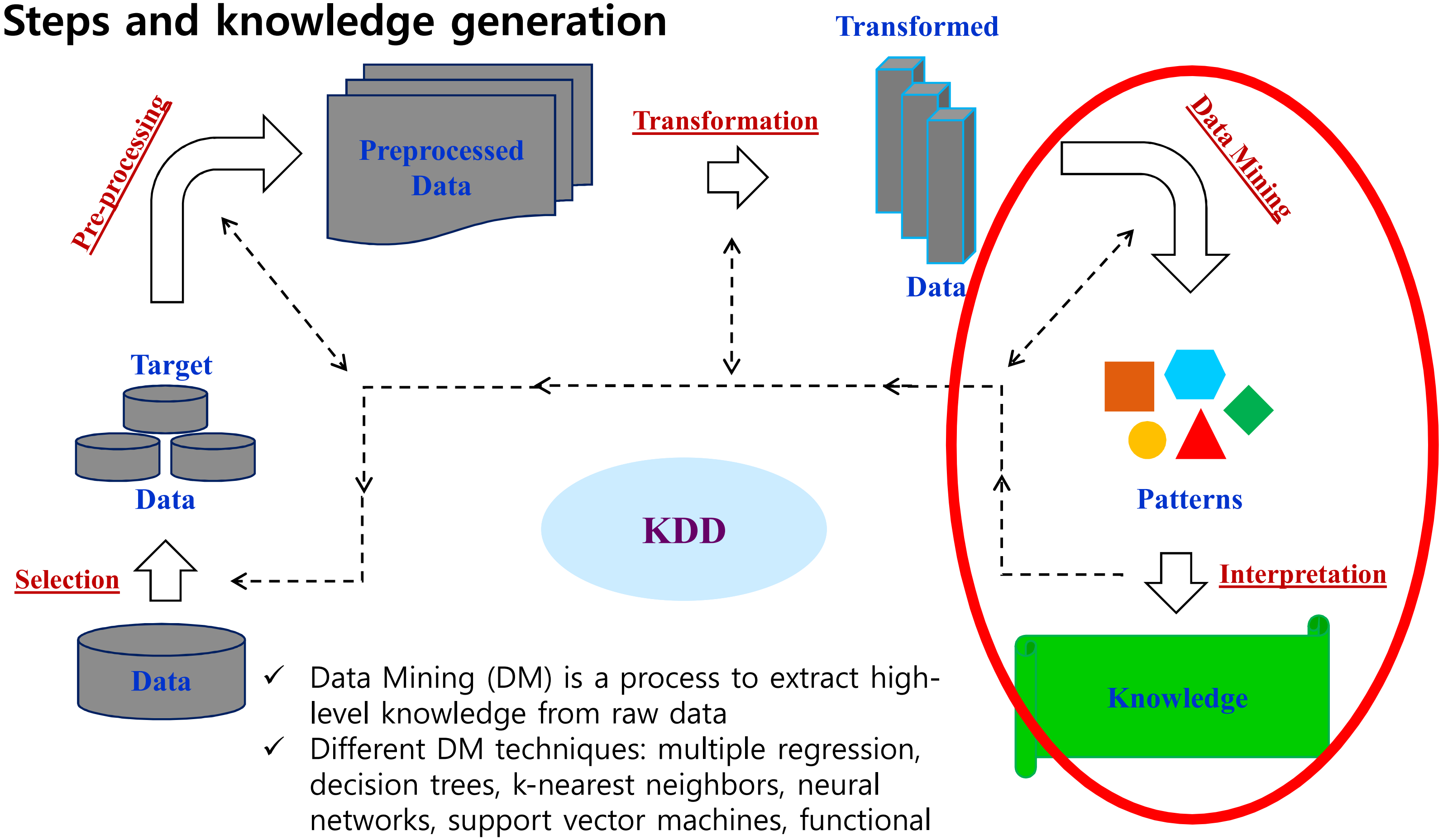
Coordinator (PI): Prof. Erol Tutumluer (Univ. of Illinois at Urbana-Champaign)



Developments in Embankments

Soft computing - Data Mining

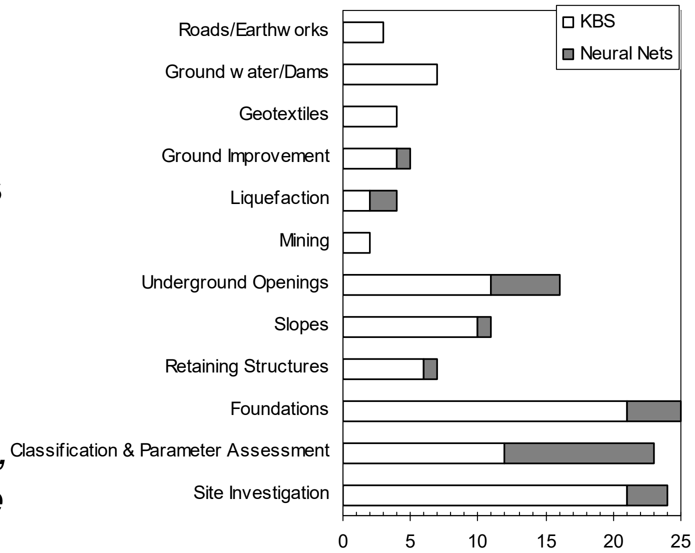
Steps and knowledge generation



- ✓ 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*



(Toll 1996)

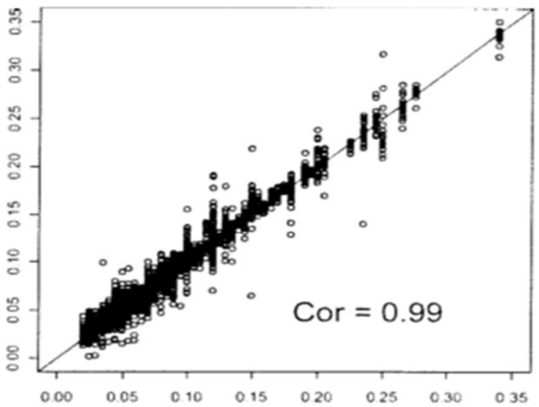
Tinoco, J.; Gomes Correia, A.; Cortez, P. Application of data mining techniques in the estimation of the uniaxial compressive strength of jet grouting columns over time, Construction and Building Materials 25, 3: 1257 - 1262. DOI: 10.1016/j.conbuildmat.2010.09.027.

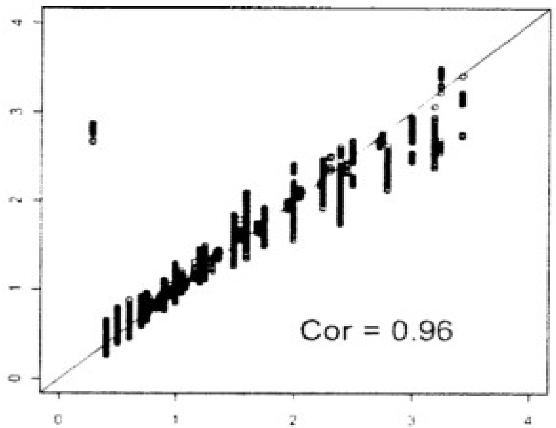
Tinoco ,J., Gomes Correia, A., Cortez, P. A novel approach to predicting young's modulus of jet grouting laboratory formulations over time using data mining techniques. Engineering Geology, 169:50–60, 2014. DOI: http://dx.doi.org/10.1016/j.enggeo.2013.11.015.

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.



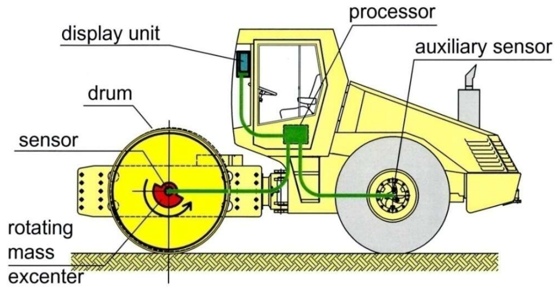


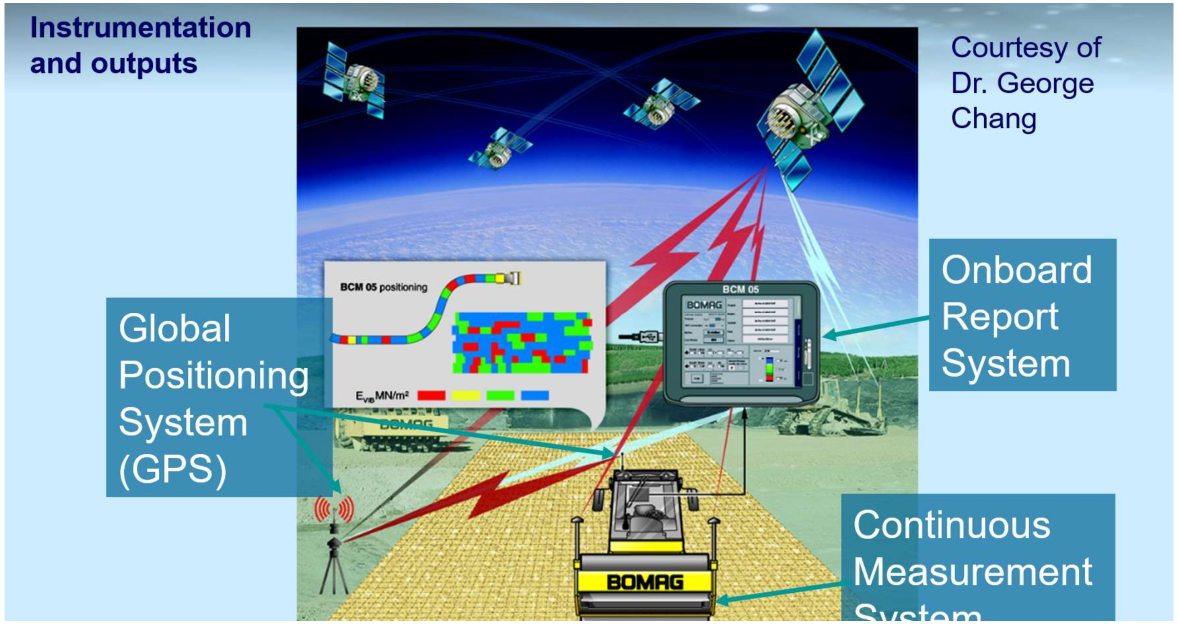
Predicted values vs. observed values for: Q/S parameter (left); e*V value (right)

Gomes Correia, A., Cortez, P., Tinoco, J., Marques, R. (2013). Artificial intelligence applications in transportation geotechnics. ASCE-Geotechnical and Geological Engineering, 31 (3), pp. 861-879.

Developments in Embankments

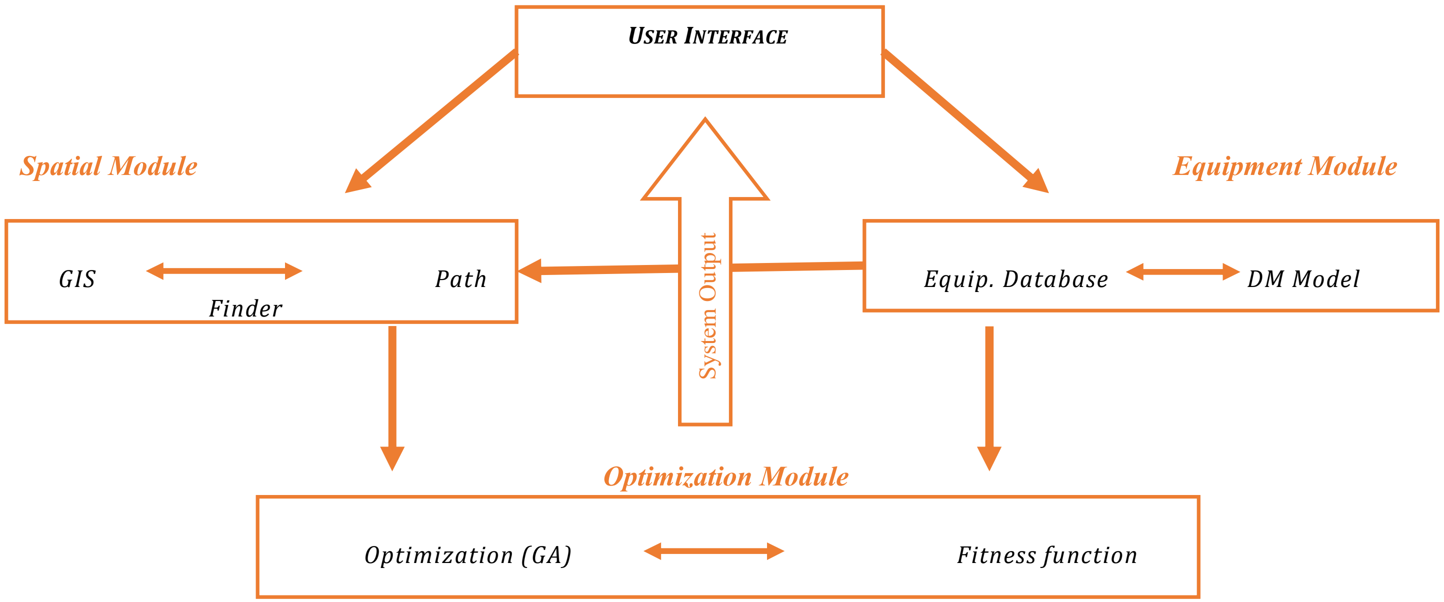
Requirements for CCC rollers





Related instrumentation already available in other equipments for earthworks

Proposed system architecture



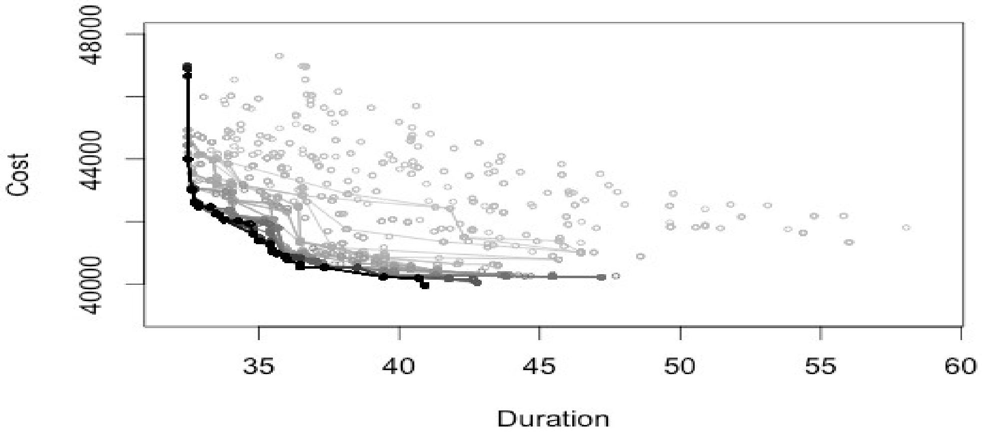
Gomes Correia, A., Magnan, J.-P. (2012). Trends and challenges in earthworks for transportation infrastructures (2012) Advances in Transportation Geotechnics II - Proceedings of the 2nd International Conference on Transportation Geotechnics, ICTG 2012, pp. 1-12.

Lição Manuel Rocha 2016

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

ISSMGE 2nd Proctor Lecture

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

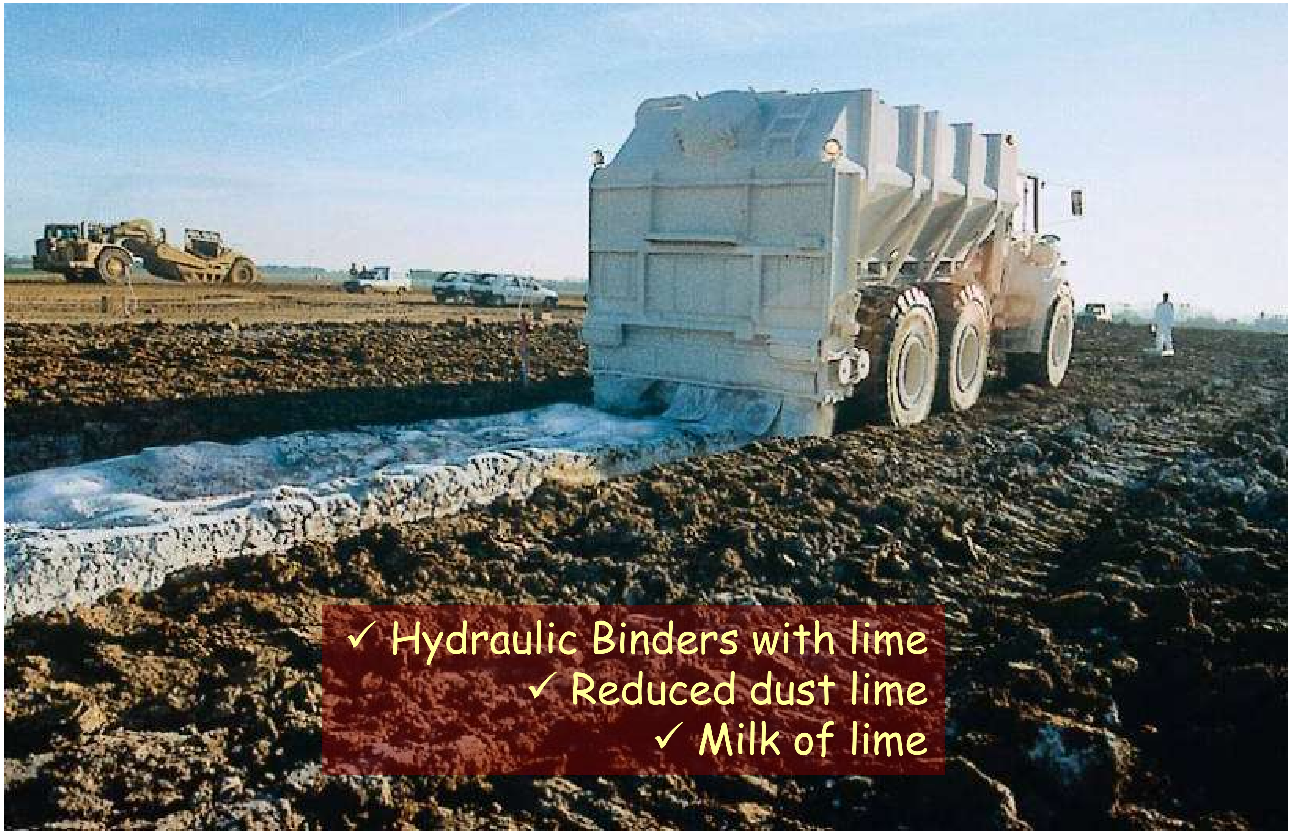
2006

Courtesy of Daniel Puiatti (Lhoist)

Developments in structural layers

Soil stabilization

… The binders have changed



Developments in structural layers

Soil stabilization

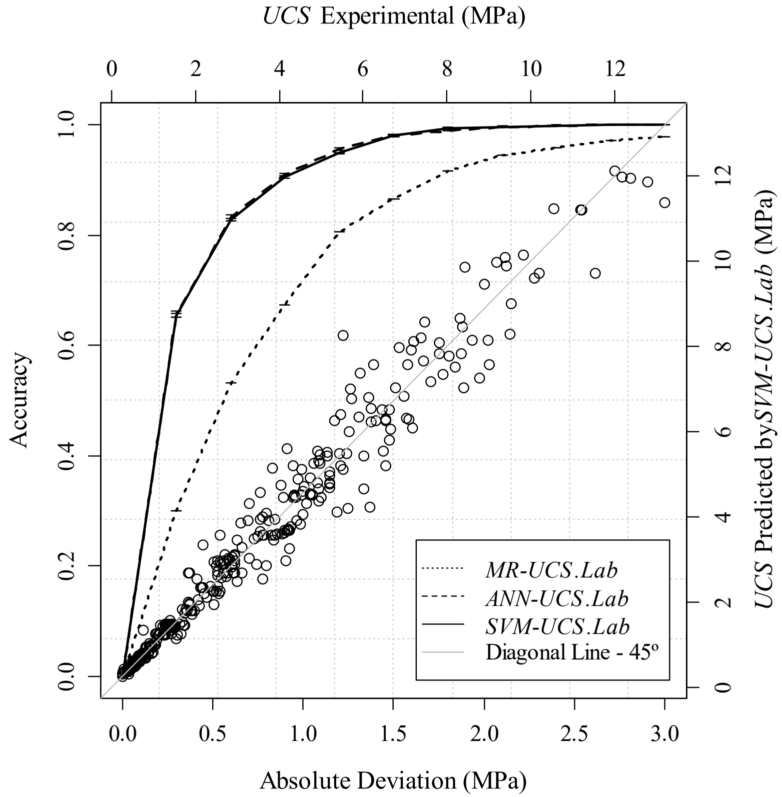
Soils of laboratory studies

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

Developments in structural layers

Soil stabilization

UCS prediction based soft computing techniques



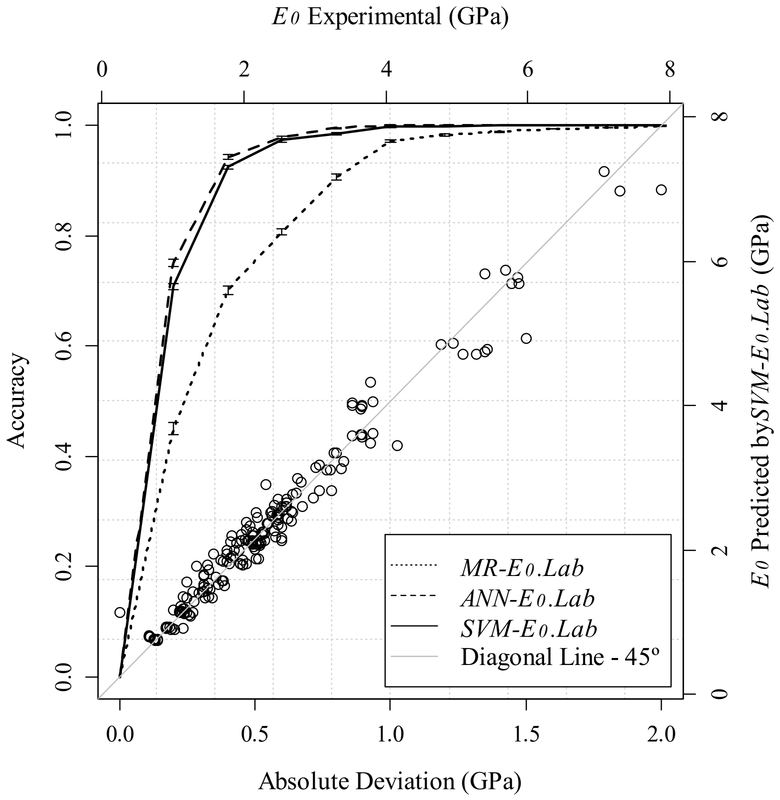
❖ ANN and SVM algorithms shows a high performance in both UCS prediction of laboratory soil-cement mixtures ($R^2 \geq 0.97$);

❖ Both ANN and SVM present a very similar performance, which is significantly better than MR model.

Developments in structural layers

Soil stabilization

E_0 prediction based soft computing techniques

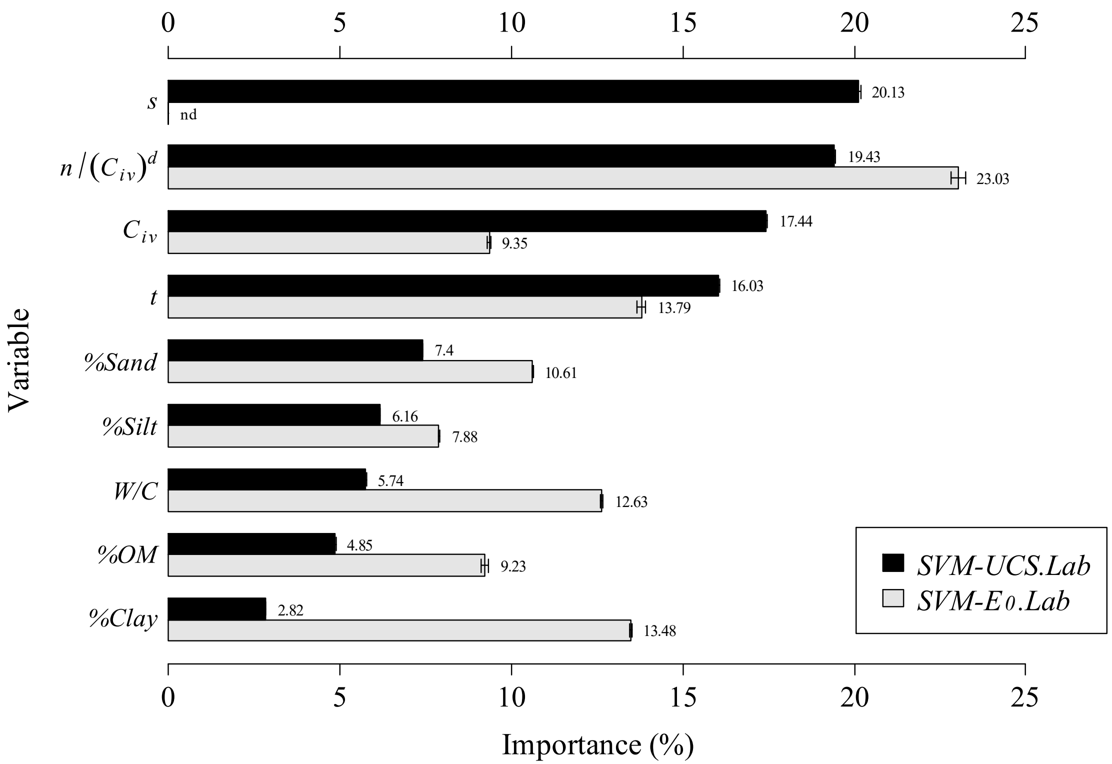


❖ Very high accuracy in E_0 prediction of laboratory soil-cement mixtures ($R^2 \geq 0.96$), either by ANN or SVM algorithms.

Developments in structural layers

Soil stabilization

UCS and E_0 prediction – relative importance of parameters



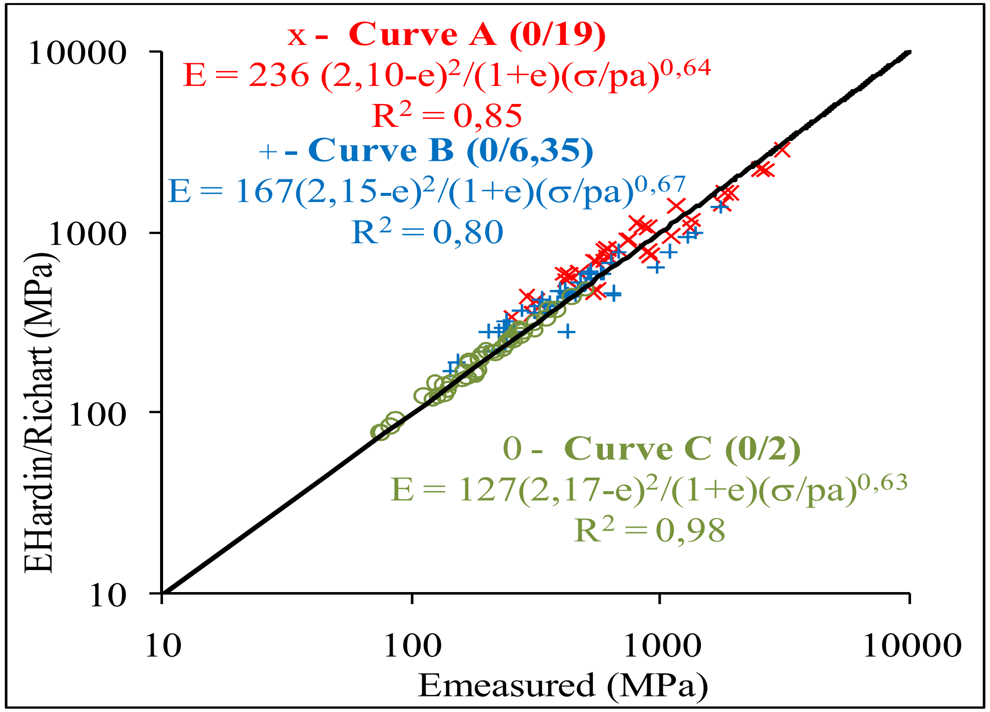
❖ $n/(C_{iv})^d$ is the key variable in both mechanical properties prediction of laboratory soil-cement mixtures.

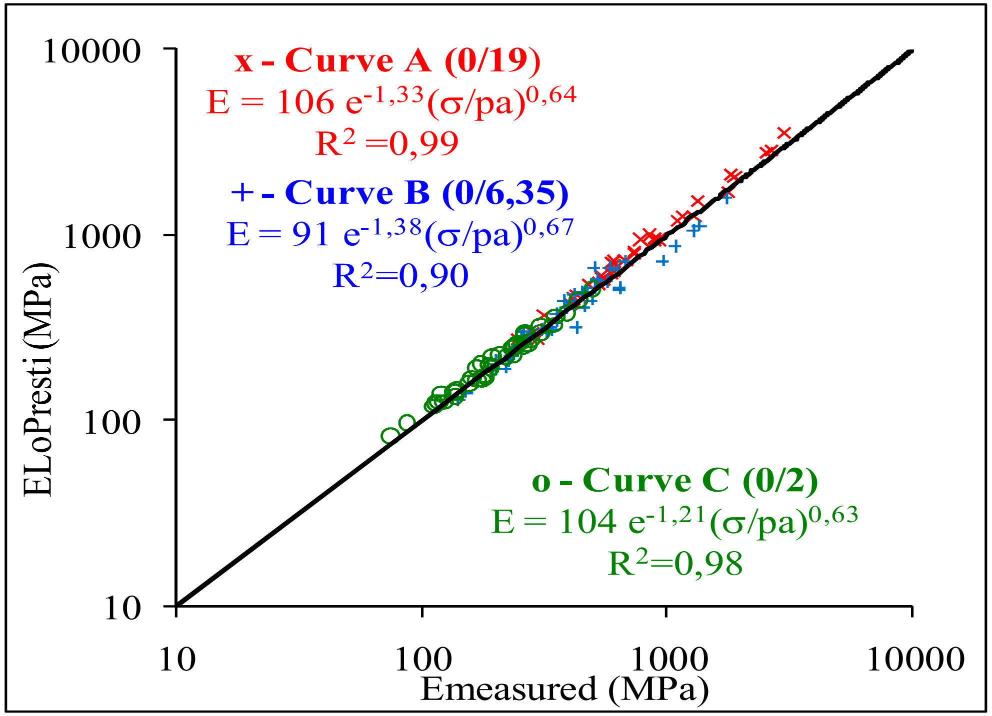
❖ In UCS study the *t, C_{iv} and s also have a strong influence.*

❖ *S*oil properties are apparently more relevant in stiffness prediction of laboratory soil-cement mixtures than in strength study.

Developments in structural layers

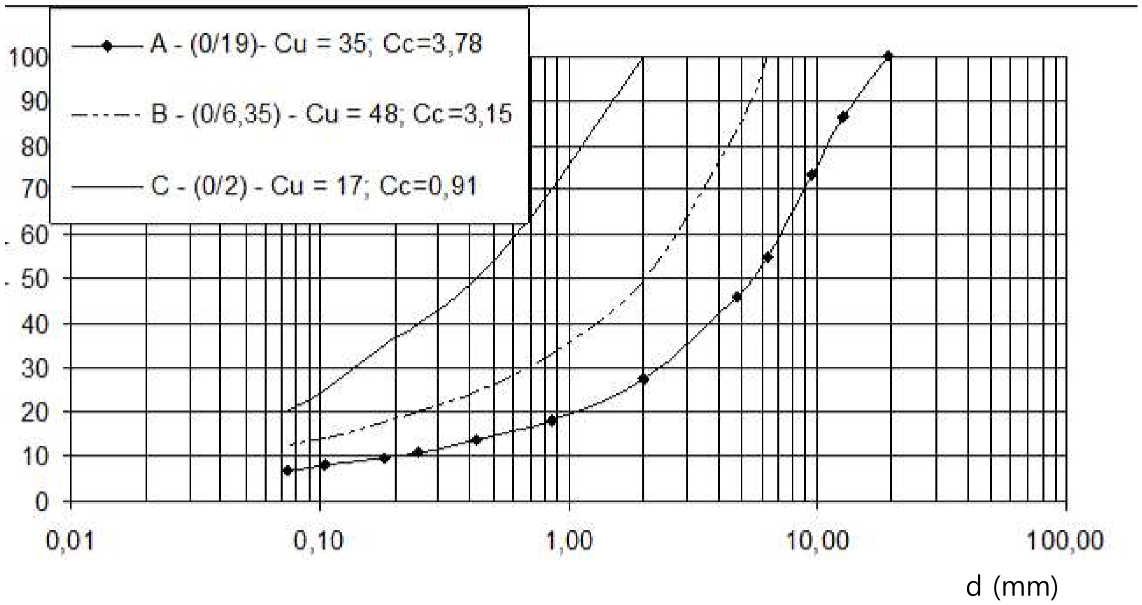
Unbound Granular materials



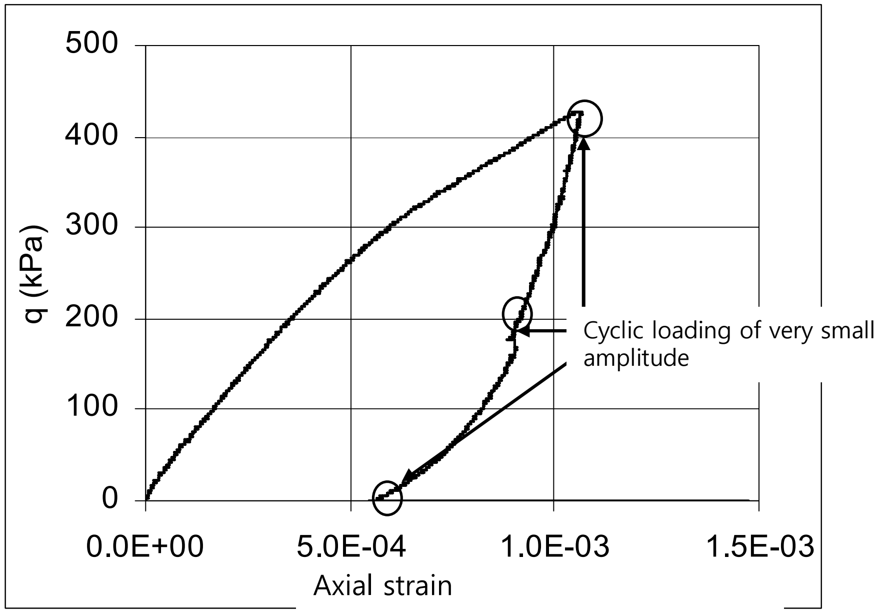


Developments in structural layers

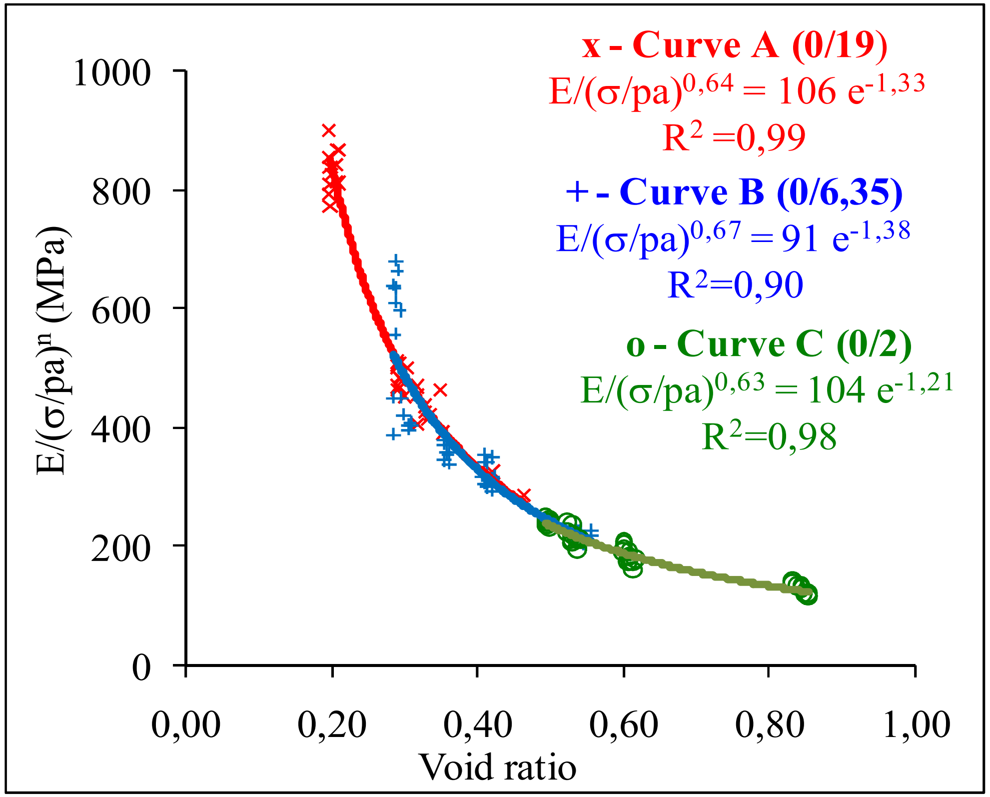
Unbound Granular materials

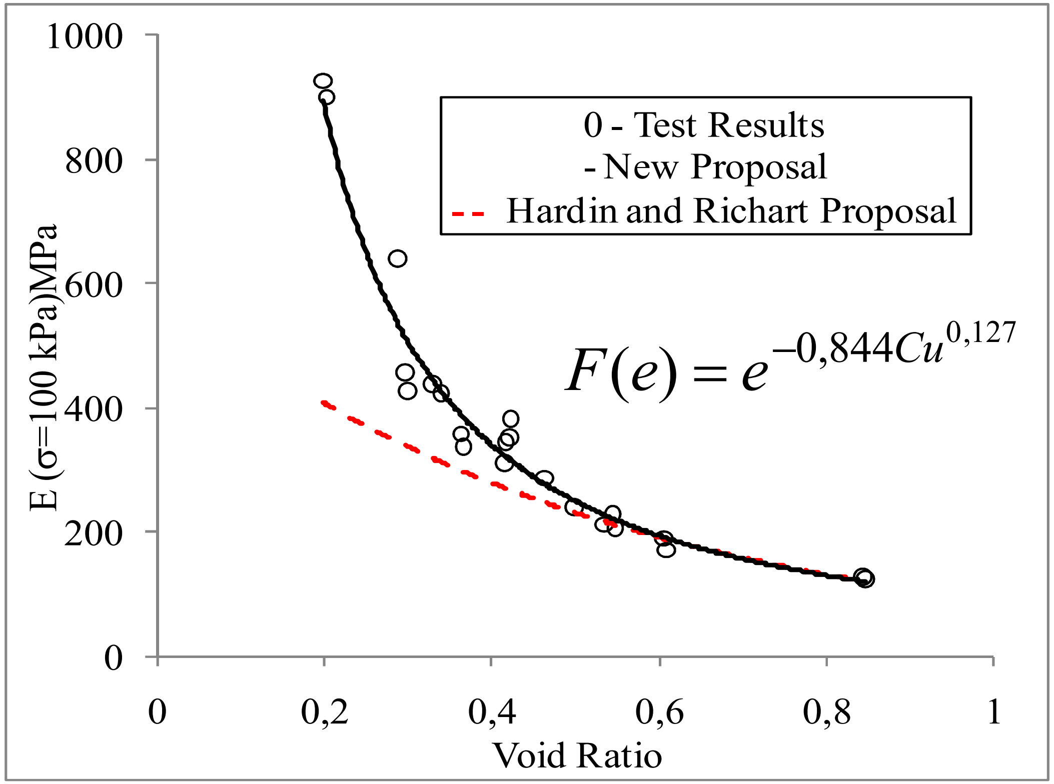


Precision triaxial cyclic loading
(Local strain measurements – LDT)



ISSMGE 2nd Proctor Lecture

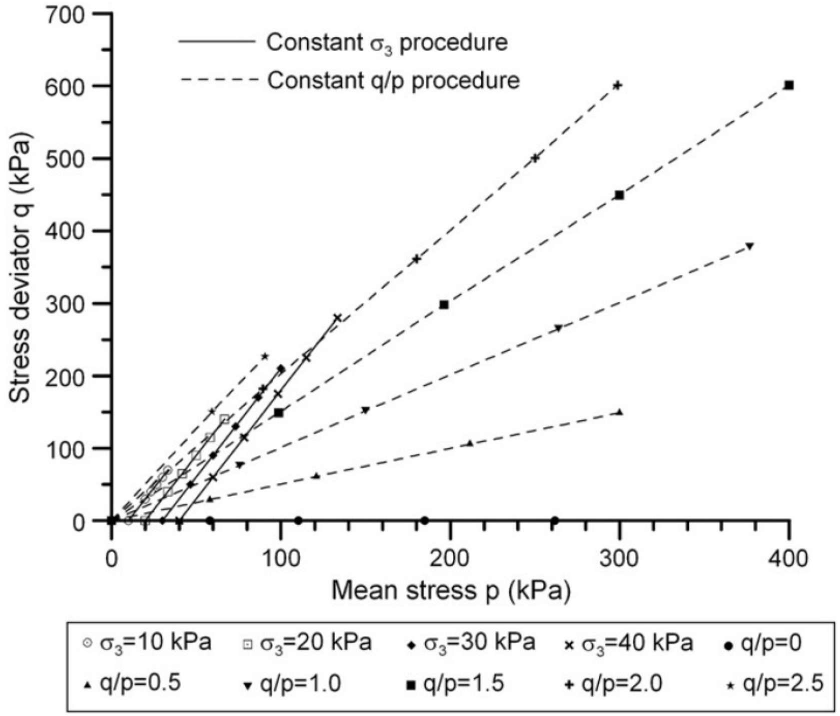


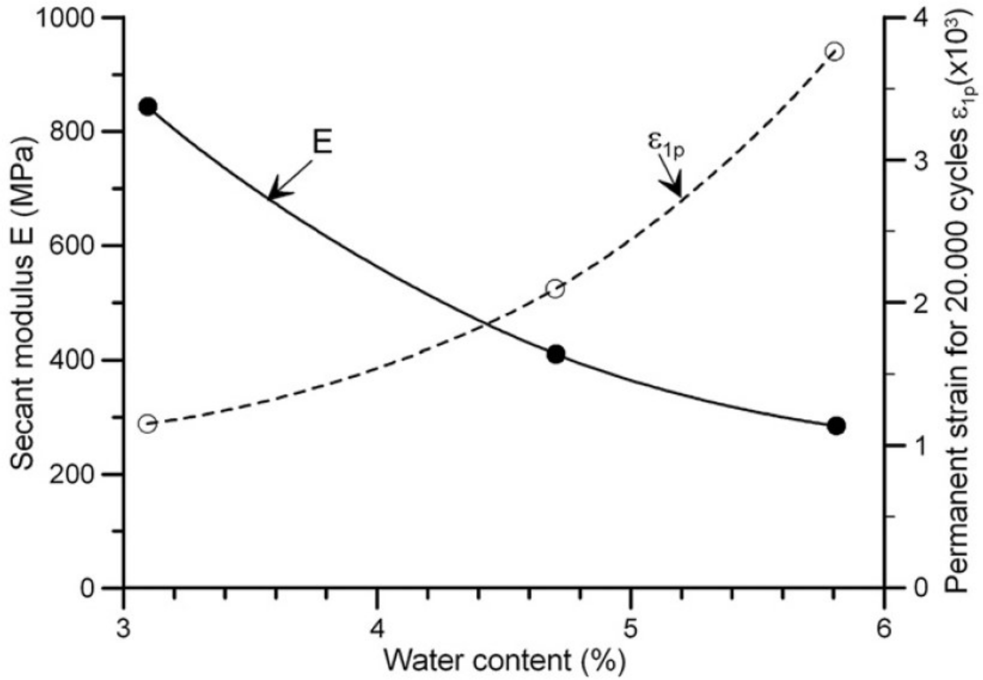


Developments in structural layers

Non traditional materials; importance of compaction parameters

Coronado, O., Caicedo, B., Taibi, S., Gomes Correia, A., & Fleureau, J. -. (2011). A macro geomechanical approach to rank non-standard unbound granular materials for pavements. Engineering Geology, 119(1-2), 64-73.



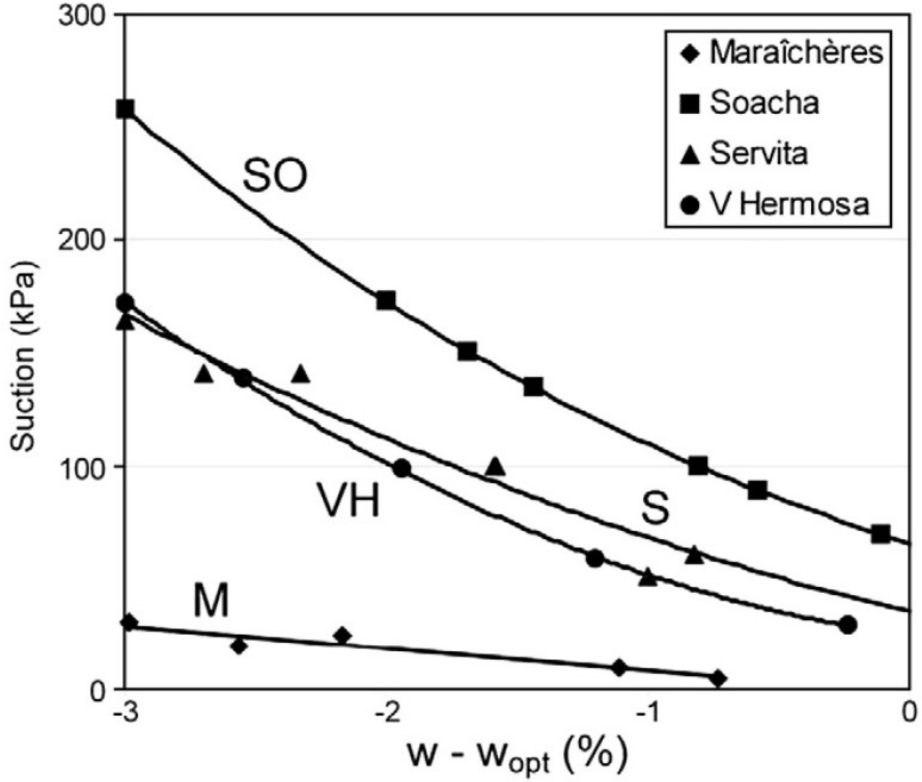


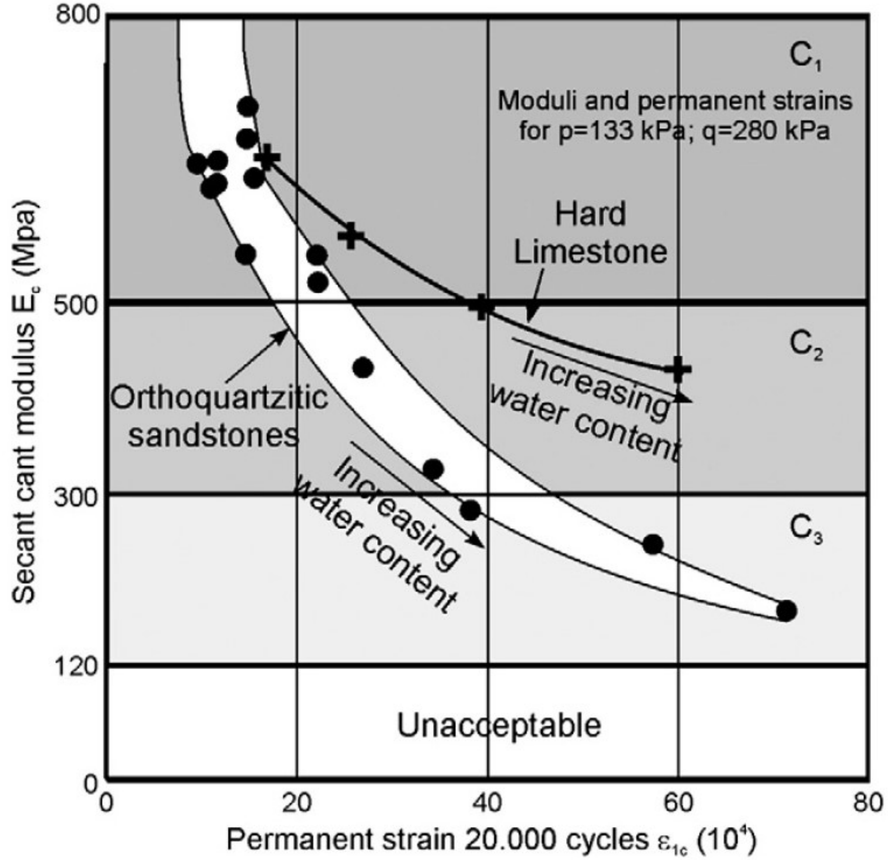
Secant modulus and permanent strain with water content - “Vista Hermosa” material.

Developments in structural layers

Non traditional materials; importance of compaction parameters

Coronado, O., Caicedo, B., Taibi, S., Gomes Correia, A., & Fleureau, J. -. (2011). A macro geomechanical approach to rank non-standard unbound granular materials for pavements. Engineering Geology, 119(1-2), 64-73.

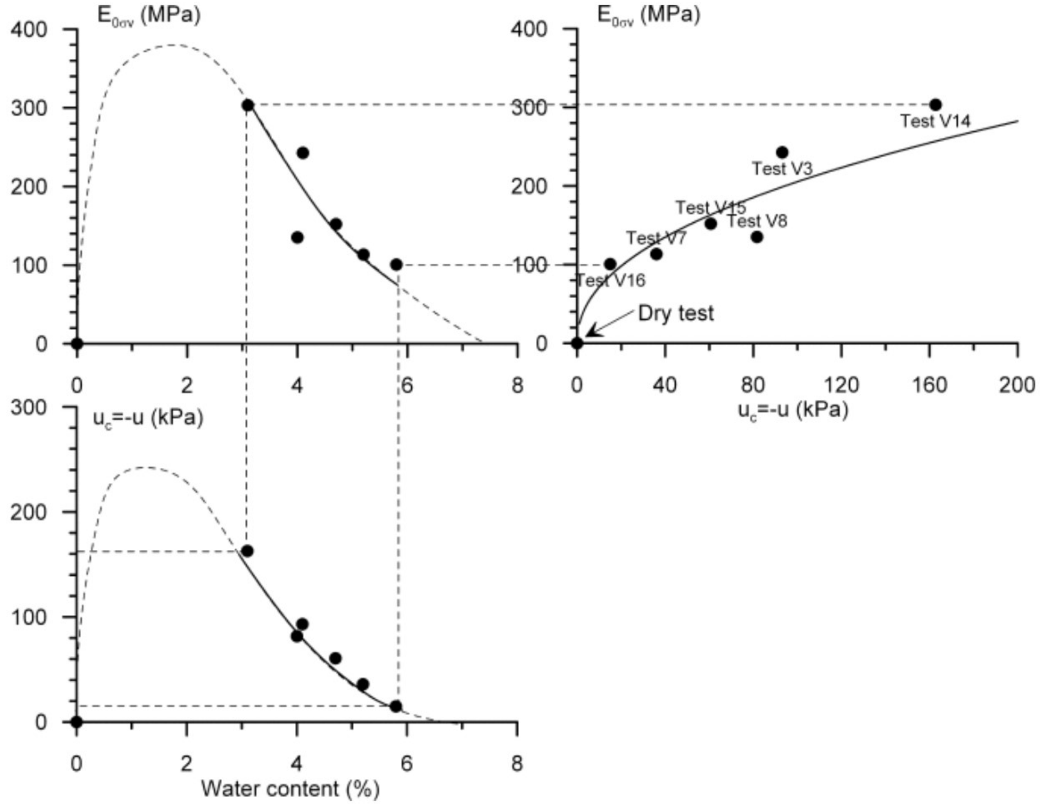


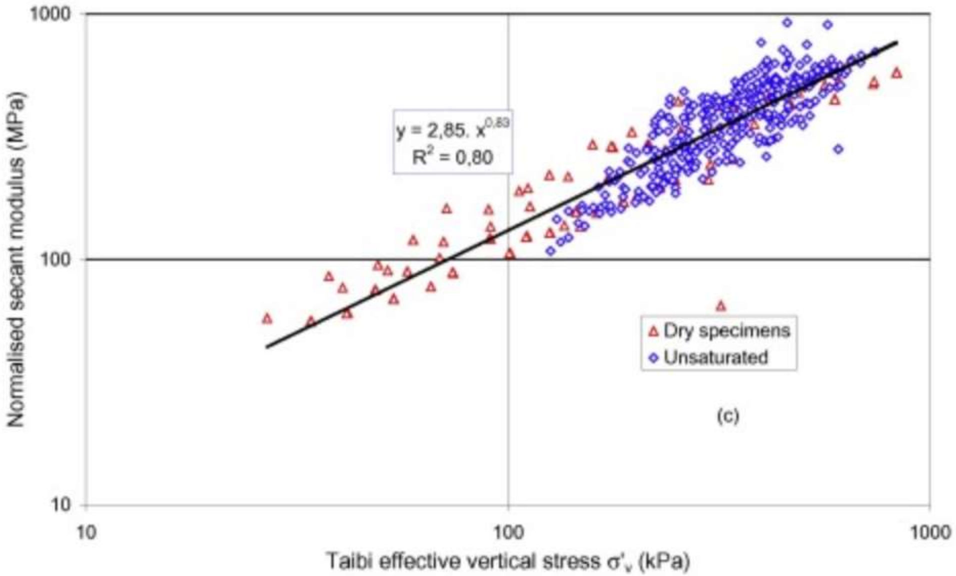


Developments in structural layers

Coronado, O., Caicedo, B., Taibi, S., Gomes Correia, A., Souli, H., & Fleureau, J. -. (2016). Effect of water content on the resilient behavior of non standard unbound granular materials. Transportation Geotechnics, 7, 29-39

Non traditional materials; importance of compaction parameters





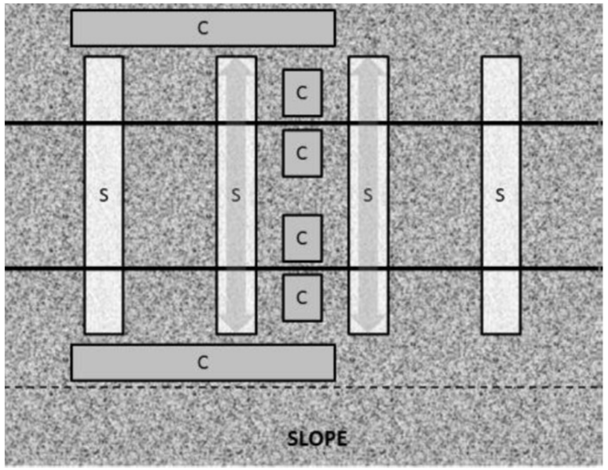
(Taïbi, 1994): $g(s) = \sigma_u(s)$; derived from an elementary calculation based on Laplace law of a regular arrangement of spheres with the same diameter *d*

Developments in structural layers

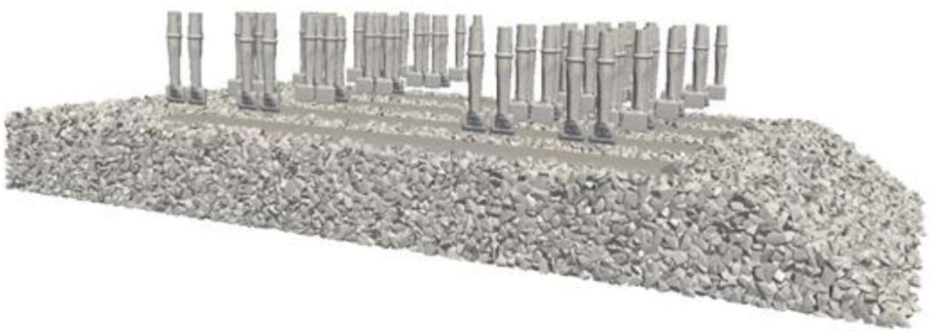
Ferellec et al., 2017

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.



sleepers (S) and compactor plates (C)

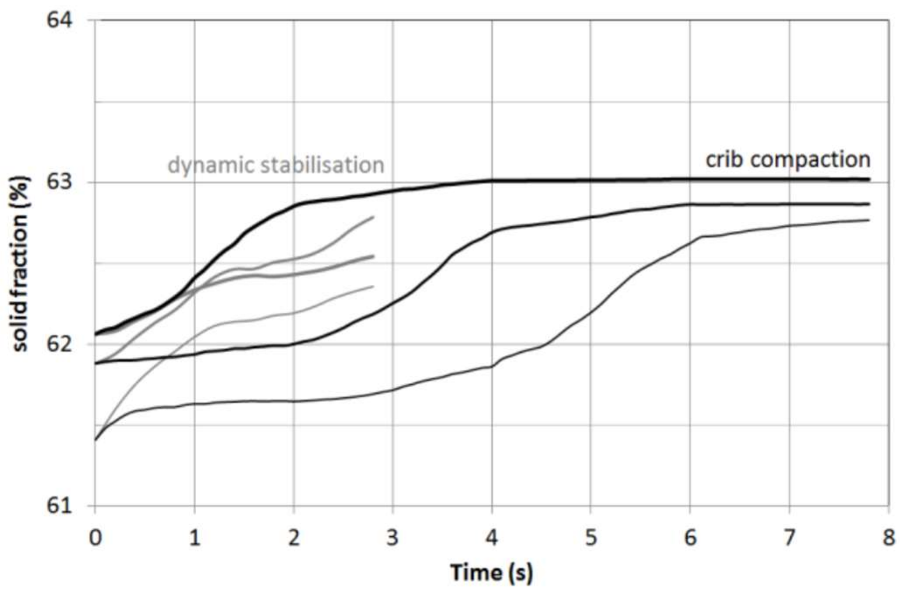


Model: NSCD (LMGC90) code - DEM

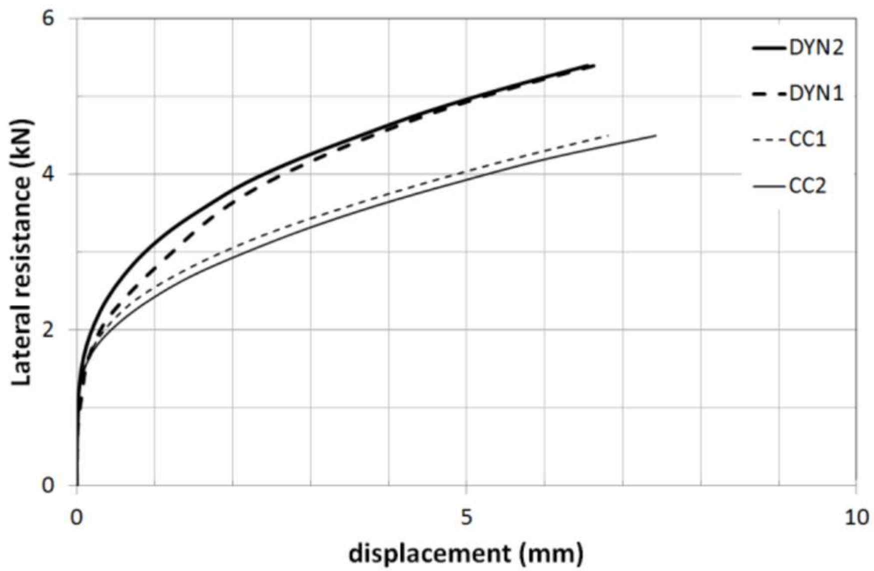
Developments in structural layers

Ferellec et al., 2017
(Sauussine team SNCF)

Numerical Simulations: dynamic, crib compaction



Dynamic stabilisation (grey) and
crib compaction (black)



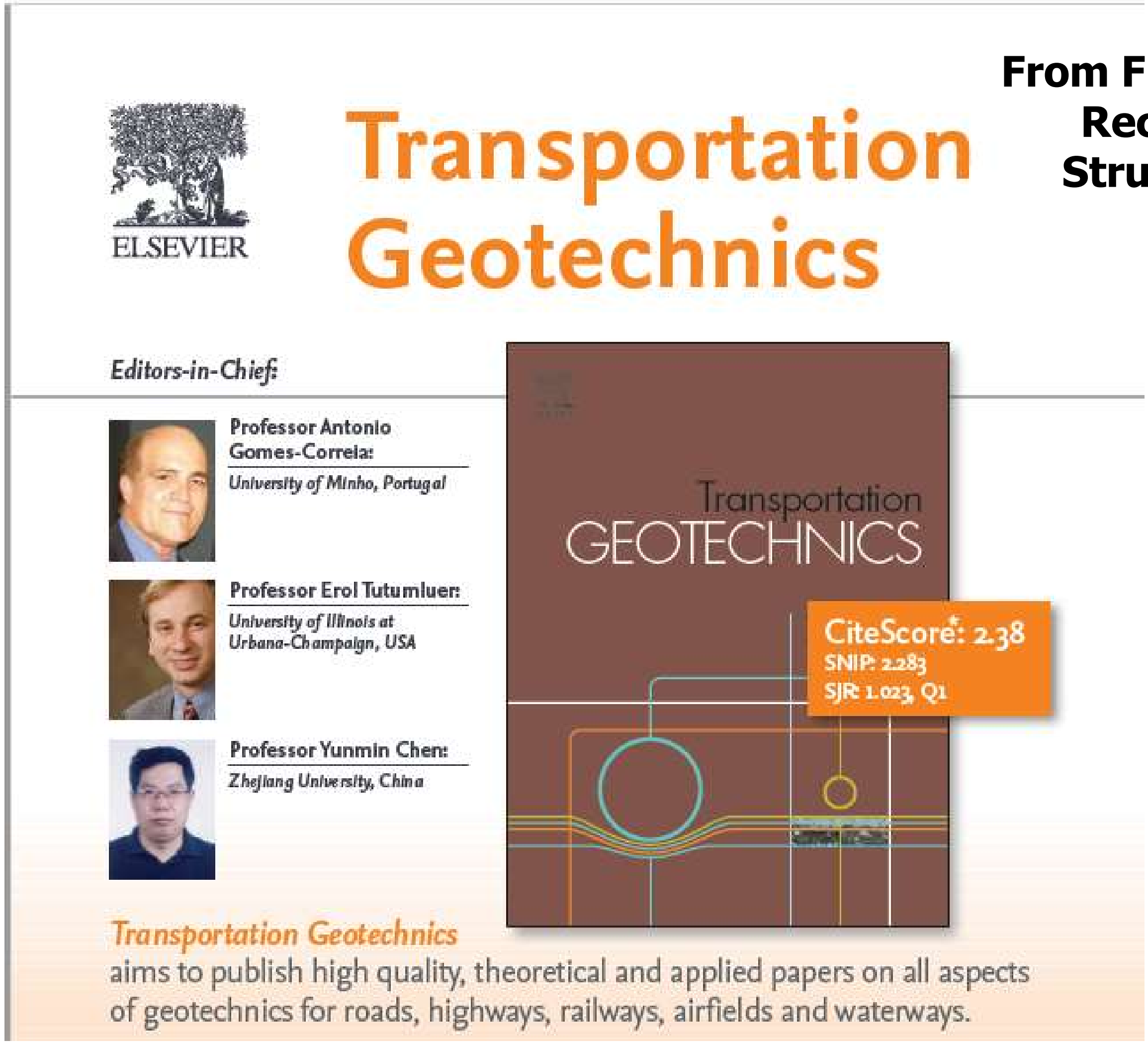
Lateral resistance as a function of sleeper displacement
for inside sleepers (1, 2):
for dynamic stabilisation (DYN) and crib compaction (CC)

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

Final remarks

- **Compaction parameters** are key índex 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, monito ring) – 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**

ISSMGE 2nd Proctor Lecture



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

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Thank you for your attention

Universidade do Minho
Escola de Engenharia

Institute for Sustainability and Innovation in Structural Engineering