PANAMERICANO 2019
Cancún Mx.

Session 13 Ground Improvement

Past, Present & Future of Ground Improvement in the Americas

Vernon R. Schaefer, Ph.D., P.E.
James M. Hoover Chair of Geotechnical Engineering
Iowa State University
Ames, Iowa, USA

vern@iastate.edu

XVI CONGRESO PANAMERICANO DE MECÁNICA DE SUELOS E INGENIERÍA GEOTÉCNICA
Ingeniería geotécnica en el siglo XXI: lecciones aprendidas y retos futuros

XVI PANAMERICAN CONFERENCE ON SOIL MECHANICS AND GEOTECHNICAL ENGINEERING
Geotechnical Engineering in the XXI century: lessons learned and future challenges

1

SCOPE OF PRESENTATION

Introduction
History of Ground Improvement
Present – Engineering of Ground Improvement
Future of Ground Improvement
Concluding Remarks

PANAMERICANO 2019
Cancún Mx.

2

PRELIMINARY QUESTIONS

What is ground improvement?

Why do we need ground improvement?

What soils are amenable to "fixing"?

What technologies do you know about?

What are the functions of ground improvement?

TERMINOLOGY

- Soil Stabilization
- Soil Improvement
- Ground Improvement
- Ground Treatment
- Ground Modification

Charles (2002) notes that the process of altering the ground is ground treatment, while the purpose of the process is ground improvement, and the result of the process is ground modification.

DEFINITION

Ground Modification

the alteration of site foundation conditions or project earth structures to provide better performance under design and/or operational loading conditions

Modified from USACE (1999)

DESIGN OPTIONS

With difficult ground conditions:

1. Bypass the poor ground – relocate or use a deep foundation
2. Remove and replace unsuitable geomaterials
3. Design structure to handle poor ground
4. Modify (improve) soils in-place

DEMANDS for USE of UNSUITABLE SOILS

- Civilization and urbanization
- Increased demands for use of land for better living and transportation
- Suitable construction sites less available

→ Use of unsuitable sites

An unsuitable site consists of problematic geomaterials and/or geotechnical conditions.

HISTORICAL OVERVIEW

- Soil is nature's most abundant construction material
- Used for engineering works since the beginning of time

Ancient Ziggurats

HISTORICAL OVERVIEW

Soil, nature's most abundant construction material, has been used by man for his engineering works since prior to the beginnings of recorded history. Virtually all construction is done on, in, or with soil, but not always are the natural soil conditions adequate to accomplish the work at hand. The basic concepts of soil improvement—densification, cementation, reinforcement, drainage, drying, and heating—were developed hundreds or thousands of years ago and remain unchanged today (ASCE 1978).

EARLY DEVELOPMENTS

- Roadways – compaction & drainage
- Fortifications - reinforcement
- Pre-Terzaghi most geotechnical design and construction was by trial and error, based on precedent and empirical rules
- Industrial Revolution and invention of machines allowed significant improvements in quality and quantity of work undertaken

SOIL COMPACTION

- Various compaction means practiced in road building back to Roman times
- 1700s – work in France & England on improving pavement subgrades and subbase layers
- Horse drawn rollers introduced in France in 1830s; steamrollers in 1860s
- Sheepsfoot roller introduced in USA in 1906
- Robert Proctor introduced compaction curves in 1930s
- Vibratory rollers after World War II

11

TIME LINES

Sand drains: 1926; Wick drains 1930s

Deep Dynamic Compaction: Romans, Germany USA 1930s

Vibro-Compaction: Germany 1930, USA 1936

Aggregate Columns: India 1653, France & Germany 1830

Column Supported Embankments: Europe 1984

Deep Mixing: Japan & Scandinavia 1960s

Grouting Methods: 1800s and 1900s

- Permeation: France and England in 1800s
- Compaction: USA 1950s

Reinforcing inclusions: ancient times, Henri Vidal 1960s

12

PRESENT GROUND IMPROVEMENT

GI: STATE OF THE PRACTICE

- Ground Improvement (GI) has developed markedly in past five decades—recognized sub-discipline
- GI now in routine use in geotechnical design and construction
- Impetus for GI increasing

13

GROUND IMPROVEMENT

When and where is GI an option?

- When site soils are amenable to improvement in performance
- When sufficient expertise, time, and equipment exist to accomplish the improvement, and
- Most importantly, when the costs of improving the soils are warranted compared to other available options.

14

ENGINEERING GI PROJECTS

Requires essential knowledge about:

1. Available methods and their unique characteristics
2. Ground and project conditions
3. How to design for required levels of improvement
4. Construction and QC/QA methods
5. Environmental constraints
6. Time requirements
7. Costs
8. Sustainability

15

MAIN FUNCTIONS OF GI

- Increase shear strength / bearing resistance
- Increase density
- Decrease permeability / improve drainage
- Transfer loads to more competent layers
- Control deformations (settlement, heave, distortions)
- Accelerate consolidation
- Decrease imposed loads
- Increase lateral stability
- Form seepage cutoffs or fill voids
- Increase resistance to liquefaction

These functions can be achieved in a variety of ways

16

Category	Function	Methods
Densification	Increase density, bearing capacity, and frictional strength; increase liquefaction resistance of granular soils; decrease compressibility, increase strength of cohesive soils	Vibrocompaction Dynamic compaction Blasting compaction Compaction grouting Surface compaction (including rapid impact compaction)
Consolidation	Accelerate consolidation, reduce settlement, increase strength	Preloading without drains Preloading with vertical drains Vacuum consolidation Electro-osmosis
Load Reduction	Reduce load on foundation soils, reduce settlement, increase slope stability	Geofoam Foamed concrete Lightweight fills, tire chips, etc. Column supported embankments with load transfer platforms
Reinforcement	Inclusion of reinforcing elements in soil to improve engineering characteristics; provide lateral stability	Mechanically stabilized earth Soil nailing/anchoring Micro piles Columns (aggregate piers, stone columns, jet grouting, etc.) Fiber reinforcement Geosynthetic reinforced embankment

17

17

Category	Function	Methods
Chemical Treatment	Increase density, increase compressive and tensile strength, fill voids, form seepage cutoffs	Permeation grouting with particulate or chemical grouts Bulk infilling Jet grouting Compaction grouting Deep soil mixing-wet and dry Fracture grouting Lime columns
Thermal stabilization	Increase shear strength, provide cutoffs, reduce liquefaction potential	Ground freezing Ground heating and vitrification
Biotechnical stabilization	Increase strength, reinforcement	Vegetation in slopes as reinforcing Microbial methods
Miscellaneous	Remediate contaminated soils	Electrokinetic methods, chemical and bio-chemical methods

18

18

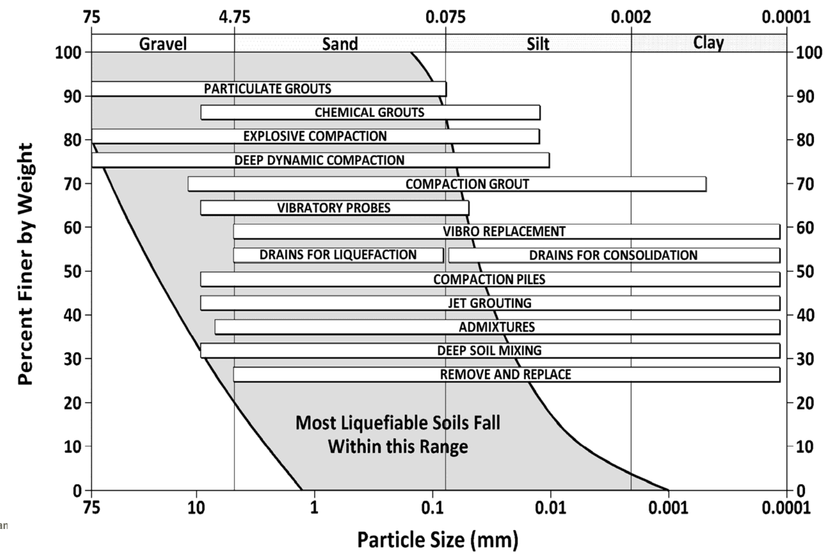
SELECTION CRITERIA – 1

1. The operational criteria for the facility; e.g. stability requirements, settlement criteria. These criteria establish the level of improvement required in terms of soil properties.
2. The area, depth, and total volume of soil to be treated
3. The soil type to be treated and its initial properties
4. Depth to groundwater table
5. Availability of materials, e.g., sand, water, admixtures, reinforcing elements.
6. Availability of specialized equipment and skilled labor force.

SELECTION CRITERIA – 2

7. Construction and environmental factors; e.g., site accessibility and constraints, waste disposal, effects on adjacent facilities and structures.
8. Local experience and preferences; politics and tradition.
9. Time available
10. Cost; generally construction cost, but also life-cycle costs

AVAILABLE GI METHODS FOR VARIOUS SOIL TYPES



Panan

21

GROUND IMPROVEMENT DESIGN

Dependent upon function of improvement and method(s) selected to carry out the function
Design Procedures vary with technology and function and may be:

1. Well established
2. Variety of published
3. Proprietary
4. Developing

Panamericano 2019 | Cancún 22

PANAMERICANO 2019 Cancún Mx.

22

Categories of Input and Output Items for Analysis and Design Procedures	Example Items
Performance Criteria/Indicators	Minimum FoS values, load and resistance factor values, allowable settlements, allowable lateral deformations, reliability, drainage, time
Subsurface Conditions	Stratigraphy, ground water level, particle size distribution, plasticity, unit weight, relative density, water content, strength, compressibility, chemistry, organic content, variability
Loading Conditions	Traffic load, embankment pressure, structure loads, earthquake acceleration and duration, water pressures
Material Characteristics	Unit weight, water content, particle size distribution, internal friction angle, shear strength, inclusion dimensions, compressive strength, tensile strength, compressibility, modulus, stiffness, interface friction angle, permeability, equivalent opening size
Construction Techniques	Method of installation and/or densification, e.g., wick drains, vibrocompaction
Geometry	Diameter, spacing, depth, thickness, length, area, slope

23

GROUND IMPROVEMENT QC/QA

Dependent upon function of improvement and method(s) selected to carry out the function

QC/QA Procedures:

1. Construction data records
2. Surface settlement & heave
3. Sampling and testing of treated soils
4. In situ testing (penetration & shear wave)
5. Pore pressure measurements
6. In situ hydraulic conductivity
7. Lateral movements

Arguably the critical limiting factor for some methods

Panamericano 2019 | Cancún 24

PANAMERICANO 2019 Cancún Mx.

24

PERFORMANCE OF IMPROVED GROUND

- Experience in use of well-established GI methods in "conventional" applications such as bearing capacity improvement, slope stabilization, precompression and acceleration of consolidation, liquefaction mitigation and construction of seepage barriers has shown that the required performance can be obtained if (1) the appropriate method is chosen for the problem and (2) the design and construction are done well.
- A common "trouble spot" is the difficulty in verifying that the desired level of improvement has been obtained, emphasizing again the need for a well-designed and implemented QC/QA program.

GI FEASIBILITY EVALUATION

- Feasibility for a project need depends on
  - ❖ Function of modification
  - ❖ Method selected
- Feasibility evaluation includes
  - ❖ Technical issues
  - ❖ Project development/delivery methods
  - ❖ Performance criteria & QA methods
  - ❖ Non-technical issues

SURFACE DENSIFICATION

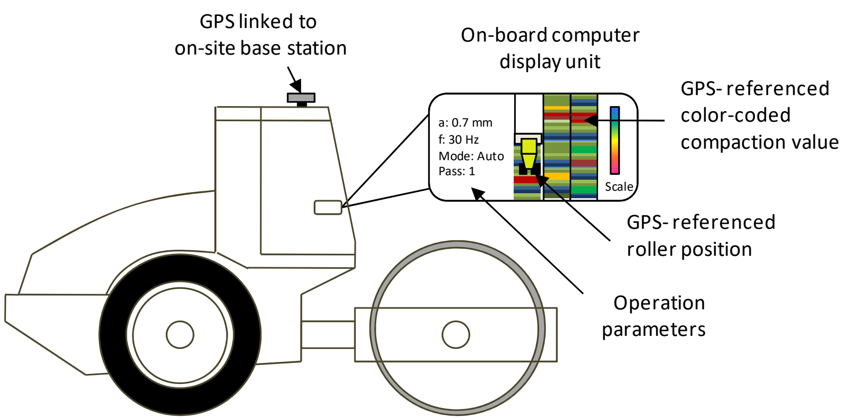
Panamericano 2019 | Cancún 27

PANAMERICANO 2019
Cancún Mx.

27

SURFACE DENSIFICATION

Intelligent Compaction:
Roller Integrated Compaction Monitoring



Machine-integrated sensors to measure drum/machine response to soil behavior

Panamericano 2019 | Cancún 28

PANAMERICANO 2019
Cancún Mx.

28

SURFACE DENSIFICATION

Intelligent Compaction:
Roller Integrated Compaction Monitoring

29

VACUUM PRELOADING

With and Without PVDs

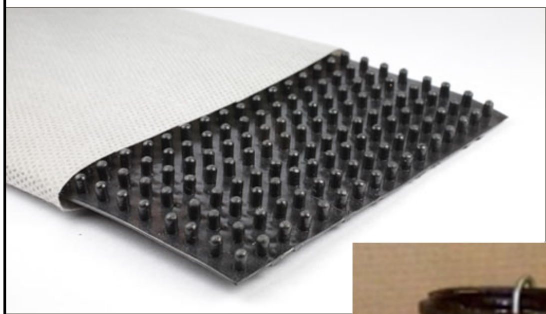
30

COLUMN SUPPORTED EMBANKMENTS

PANAMERICANO 2019
Cancún Mx.

31

EARTHQUAKE DRAINS



PVDs

32

www.GeoTechTools.org

Geo-Construction Information & Technology Selection Guidance for Project Planning & Development, Program Delivery, and Improved Infrastructure Performance

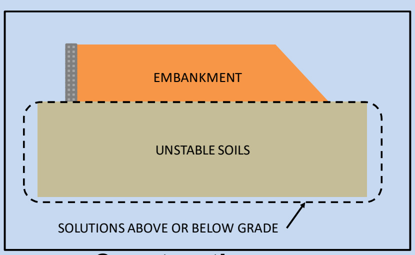
SHRP2

STRATEGIC HIGHWAY RESEARCH PROGRAM

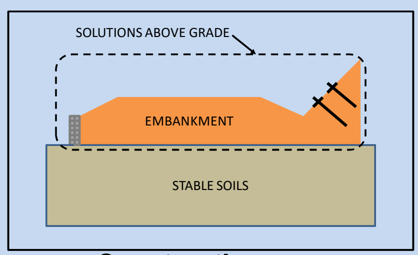
Accelerating solutions for highway safety, renewal, reliability, and capacity

33

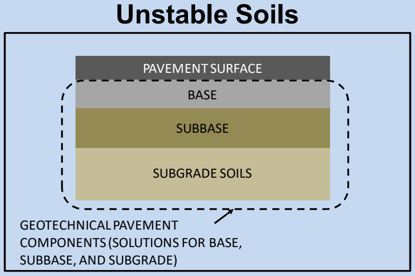
Application Areas



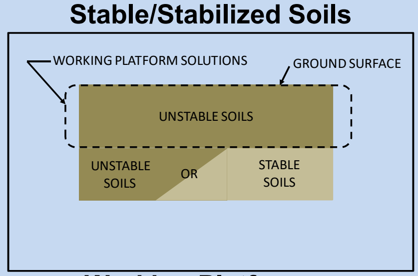
Construction over Unstable Soils



Construction over Stable/Stabilized Soils



Geotechnical Pavement Components (Base, Subbase, and Subgrade)



Working Platforms

34

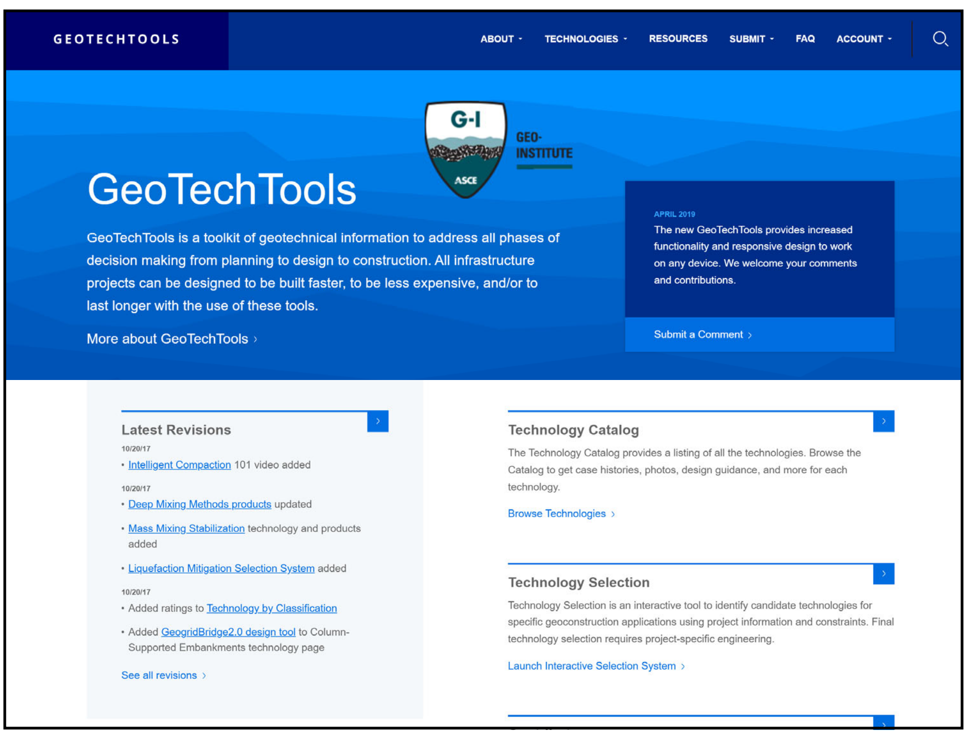
OBJECTIVES OF THE SYSTEM

1. Identify potential technologies for the four Applications. → >50 Technologies
2. Provide current, up to-date information → 8 Products/Tools for each Technology
3. Provide guidance to develop a 'short-list' of applicable technologies
4. Provide guidance for project-specific screening
5. Provide interactive, programmed system

Panamericano 2019 | Cancún 35

PANAMERICANO 2019 Cancún Mx.

35



36

VALUE ADDED

- Main product: Web based information and guidance system
- The primary value of the system is that it *collects*, *synthesizes*, *integrates*, and *organizes* a vast amount of *critically important information* about geotechnical solutions in a system that makes the information *readily accessible* to the transportation agency personnel who need it most.

PANAMERICANO 2019
Cancún Mx.

37

FUTURE OF GROUND IMPROVEMENT

"It's tough to make predictions, especially about the future."

— Yogi Berra, NY Yankees baseball player & manager

PANAMERICANO 2019
Cancún Mx.

38

FUTURE OF GROUND IMPROVEMENT

- Contractor Innovations
- Improvements in design and quality assurance
- Sustainability
- Biogeotechnical Engineering: Bio-mediated & Bio-inspired Processes

39

SUSTAINABILITY

- Practically all geotechnical construction processes rely on nonrenewable energy and material resources such as petroleum fuels, cement, steel, plastics, and other chemicals.
- Ground improvement design selection typically based on performance assessment & associated monetary cost – less importance placed on environmental impacts or societal concerns.
- Sustainability is increasingly a relevant design alternative.

40

ENVIRONMENTAL/SOCIETAL IMPACTS

- Projects often include other performance requirements
  - ❖ Aesthetics, user/occupant comfort, community impact, accessibility, and site stewardship
- Ground improvement impacts can be addressed under site sterwardship
  - ❖ Noise, wastewater, emissions, traffic interruption (vehicular and pedestrian), dust control, and potential spoil migration; health and safety of workers

Panamericano 2019 | Cancún 41

PANAMERICANO 2019 Cancún Mx.

41

CONSCIENTIOUS ACTION

- Conscientious action on the part of geotechnical designers and contractors is one way geotechnical design and construction can immediately contribute to social sustainability.
- Life cycle analysis (LCA): quantitative method to evaluate environmental impacts of a product or process.
  - ❖ Consider factors such as raw material extraction, processing, use, recycling, reuse, and ultimately, final disposal
  - ❖ Many variations on this theme: LCEA, EE, GHGs

Panamericano 2019 | Cancún 42

PANAMERICANO 2019 Cancún Mx.

42

GI SUSTAINABILITY

- Ground improvement techniques can be a sustainable geotechnical construction alternative relative to traditional foundation systems because they have the potential to reduce construction time, material use, fuel consumption, and labor.
- These four factors are directly related to the environmental impact and/or the cost of the geotechnical design and construction.

43

GI SUSTAINABILITY MODELS

- **EFFC-DFI Geotechnical Carbon Calculator**
  - ❖ Computes GHG emissions associated with deep foundation and ground improvement construction projects
  - ❖ Includes: Material manufacturing (cement, bentonite, steel, etc.), Material transportation, Worker transport to site, Equipment transportation, Equipment manufacture, Waste transportation and Waste treatment
  - ❖ Includes: Bored pile walls, Soldier pile walls, Anchors, Soil Nails, Dynamic compaction, Vibro compaction, Jet Grouting, Stone Columns, Vertical Drains, Dewatering, Underpinning, Horizontal Drilling

44

GI SUSTAINABILITY MODELS

- **SEEAM – Streamlined Energy & Emissions Assessment Model** (Shillaber et al. 2016)
  - Quantifies energy consumption & carbon dioxide (CO_2) emissions
  - Methodology to incorporate sustainability into ground improvement planning & design decision making
  - Includes energy & CO_2 emissions associated with transport of materials & wastes, equipment manufacture, site operations, construction wastes, material recycling

CHALLENGES TO GI SUSTAINABILITY

1. Geotechnical design is strongly site specific
2. Fewer design varieties are available
3. Installation process envisioned in design often not reflected in actual construction
4. Service life is often longer than that of buildings and negligible operational energy is required

(after Inui et al. 2011)

BIOGEOTECHNICAL ENGINEERING

An emerging sub-discipline in geotechnical engineering that includes:

- Bio-mediated Processes: managed and controlled through biological activity (living organisms).
- Bio-inspired Processes: biological principles to develop new, abiotic solutions (no living organism)

Center for Bio-mediated & CBBG Bio-inspired Geotechnics

Courtesy Ed Kavazanjian

PANAMERICANO 2019 Cancún Mx.

47

BIOGEOTECHNICAL PREMISE

- Nature has developed many elegant biogeotechnical processes
  - ❖ Billions of years of trial and error
- These processes can be used to address geotechnical problems

→ **We can <u>Learn from Nature</u>**

Center for Bio-mediated & CBBG Bio-inspired Geotechnics

Courtesy Ed Kavazanjian

PANAMERICANO 2019 Cancún Mx.

48

LEARNING FROM NATURE

Durable geologic deposits

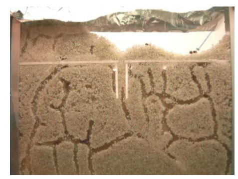
http://welcome2britain.com/white-cliffs-dover-canterbury-tour.htm

http://www.kaieteurnewsonline.com/2013/05/26/the-mole/

Resilient foundations

https://www.pinterest.com/pin/292030357067481250/

Courtesy of Carlos Santamarina



Courtesy of Carlos Santamarina

Efficient and safe penetration and tunneling

Courtesy Ed Kavazanjian

Panamericano 2019 | Cancún 49

Center for Bio-mediated & CBBG Bio-inspired Geotechnics

PANAMERICANO 2019 Cancún Mx.

49

BIOGEOTECHNICAL GI TECHNOLOGIES

- Mineral (Carbonate) precipitation
- Desaturation
- Bio-films
- Biopolymers
- Root-inspired reinforcement and foundations
- Self-motile probes

Courtesy Ed Kavazanjian

Panamericano 2019 | Cancún 50

Center for Bio-mediated & CBBG Bio-inspired Geotechnics

PANAMERICANO 2019 Cancún Mx.

50

MITIGATION OF LIQUEFACTION

Densification: Vibration, cavity expansion
- Disruptive to existing facilities

Reinforcement: Soil mixing, aggregate columns
- Not beneath existing facilities, disruptive

Grouting: Penetration, compaction grouting
- Limited applicability, expensive

➡ **No cost-effective mitigation for existing facilities**

Courtesy Ed Kavazanjian

Center for Bio-mediated & CBBG Bio-inspired Geotechnics

Panamericano 2019 | Cancún 51

PANAMERICANO 2019 Cancún Mx.

51

BIOGEOTECHNICAL LIQUEFACTION MITIGATION

Three different biogeotechnologies:
- Microbially Induced Carbonate Precipitation (MCIP)
- Microbially Induced Desaturation and Precipitation (MIDP) via denitrification
- Enzyme Induced Carbonate Precipitation (EICP) via ureolysis

Courtesy Ed Kavazanjian

Center for Bio-mediated & CBBG Bio-inspired Geotechnics

Panamericano 2019 | Cancún 52

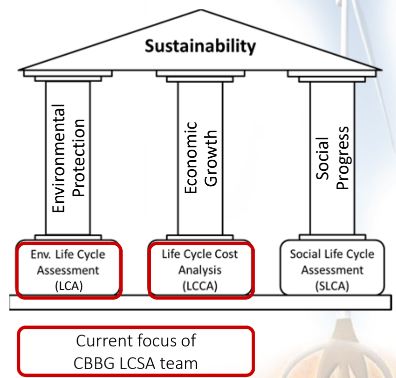
PANAMERICANO 2019 Cancún Mx.

52

Life Cycle Sustainability Assessment (LCSA)

Life Cycle Sustainability Assessment (LCSA) offers a framework to evaluate impacts to the:

- **Environment** – Environmental life cycle assessment (ELCA or LCA)
- **Economy** – Life cycle cost analysis (LCCA)
- **Society*** – Social life cycle assessment (SLCA)



* Social indicators are less developed and not widely used. Thus alternative mechanisms are used to understand social impacts

Courtesy Jason DeJong & Alissa Kendall

Center for Bio-mediated & CBBG Bio-inspired Geotechnics

53

SUMMARY & CONCLUSIONS

- Selection of suitable GI methods and optimization of their design and construction requires extensive back-ground knowledge of available ground treatment technologies and careful evaluation of several factors.
- Current state of practice is exhilarating and stimulating with great potential for improved performance and solution to difficult site and soil problems

Panamericano 2019 | Cancún 54

PANAMERICANO 2019 Cancún Mx.

54

SUMMARY & CONCLUSIONS

- GTT provides substantial information to help guide users select appropriate technologies
- The future of GI is encouraging and exciting through innovation, sustainability and biogeotechnics

PANAMERICANO 2019
Cancún Mx.

55

THANK YOU VERY MUCH FOR YOUR ATTENTION!

¡MUCHAS GRACIAS POR SU ATENCIÓN!

MUITO OBRIGADO PELA SUA ATENÇÃO!

PANAMERICANO 2019
Cancún Mx.

56