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Meeting Today's Ground Improvement Challenges.

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Meeting Today's Ground Improvement Challenges
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ABSTRACT

Many methods, materials, and design schemes can be used for improving almost any type of soil and ground conditions for many different purposes. Selecting and optimizing ground improvement methods for specific applications and projects can be challenging owing to both the many differing ground conditions that may be encountered and the vast amount of ground improvement information that is available. Two new developments that aid in meeting these challenges are described and illustrated in this paper.

"GeoTechTools.org" is a new, open-source, web-based information and guidance system for geo-construction and ground improvement technologies. Detailed information including fact sheets, case histories, photographs, design guidance, QA/QC information, cost estimating tools, and technical bibliographies pertaining to approximately 50 technologies has been compiled and is easily accessed online. The system also includes interactive guidance to aid in the selection of technologies that may be suitable for specific project needs.

Sustainability considerations are now of concern in ground improvement and earthwork construction projects. Embodied Energy (EE) and CO_2 emissions are indicators of environmental impacts. An illustrative case history is presented to show how quantified EE and CO_2 emissions can be used to aid in selection and refinement of ground improvement technologies and designs for more sustainable development.

INTRODUCTION

Laurits Bjerrum was a true "Giant of Geotechnics" in the Twentieth Century. I was privileged to benefit from his mentoring and friendship when I was one of the first overseas visitors to the Norwegian Geotechnical Institute during the summer of 1953, while still a graduate student at M.I.T. To be invited to present this memorial lecture is a great honor and a highlight of my career.

Ground Improvement is now a major subdiscipline within Geotechnical Engineering. There are many methods, materials, and design schemes that can be used for improving almost any type of soil and ground conditions for many purposes; for example: new earthwork and infrastructure construction, environmental cleanup and enhancement, mitigation of risks and recovery from natural disasters, and for restoration and upgrading existing structures and facilities.

Major categories, functions, and methods of ground improvement are summarized in Table 1. Specific information, material properties, and design and performance requirements that must be known or specified for a successful ground improvement project are summarized in Table 2.

Experience has shown that the required performance of improved ground can be obtained if (1) the appropriate method is chosen for the problem and existing soil conditions, and (2) the design and construction are done well. A common "trouble spot," however, is the difficulty in verifying that the desired level of improvement has been obtained, emphasizing the need for carefully prepared specifications and a well-designed and implemented QC/QA program.

In this paper two important new and continuing developments in Ground Improvement are described and illustrated:

1. “GeoTechTools.org,” a new, open source, web-based information and guidance system for geo-construction and ground improvement technologies, and
2. Some sustainability considerations in ground improvement method selection, design, and construction operations.

PART I: GeoTechTools.org

GeoTechTools.org was developed as a comprehensive web-based information and guidance system for embankments, ground improvement, and pavement applications as part of the second Strategic Highway Research Program sponsored by the U.S. Transportation Research Board. The studies that comprised this project were carried out by researchers at several universities and engineers in professional practice. More detailed information about the organization of this project and the participants can be found on the GeoTechTools.org web site.

The objectives of the system are to:

1. Identify potential ground improvement and construction technologies for different applications. The system now provides information for almost 50 technologies.
2. Provide current, up to-date information. Eight categories of information are provided for each technology, as shown in the “tool box” in Figure 1.
3. Provide guidance to develop a ‘short-list’ of applicable technologies for different types of problems, projects and ground conditions.
4. Provide guidance for project-specific screening purposes.
5. Provide an easy to use interactive, programmed system.

The technologies that are included in the system as of December 31, 2014 are the following:

1. Aggregate Columns
2. Beneficial Reuse of Waste Materials
3. Bio-Treatment for Subgrade Stabilization
4. Blasting Densification
5. Bulk-Infill Grouting
6. Chemical Grouting/Injection Systems
7. Chemical Stabilization of Subgrades and Bases
8. Column-Supported Embankments
9. Combined Soil Stabilization with Vertical Columns
10. Compaction Grouting
11. Continuous Flight Auger Piles
12. Deep Dynamic Compaction
13. Deep Mixing Methods
14. Drilled/Grouted and Hollow Bar Soil Nailing
15. Electro-Osmosis
16. Excavation & Replacement
17. Fiber Reinforcement in Pavement Systems
18. Geocell Confinement in Pavement Systems
19. Geosynthetic Reinforced Construction Platforms
20. Geosynthetic Reinforced Embankments
21. Geosynthetic Reinforcement in Pavement Systems
22. Geosynthetic Separation in Pavement Systems
23. Geosynthetics in Pavement Drainage
24. Geotextile Encased Columns
25. High-Energy Impact Rollers
26. Hydraulic Fill with Geocomposite and Vacuum Consolidation
27. Injected Lightweight Foam Fill

28. Intelligent Compaction
29. Jet Grouting
30. Lightweight Fill
31. Mass Mixing Methods
32. Mechanical Stabilization of Subgrades and Bases
33. Mechanically Stabilized Earth Wall System
34. Micropiles
35. Onsite Use of Recycled Pavement Materials
36. Partial Encapsulation
37. Prefabricated Vertical Drains and Fill Preloading
38. Rapid Impact Compaction
39. Reinforced Soil Slopes
40. Sand Compaction Piles
41. Screw-in Soil Nailing
42. Shoot-in Soil Nailing
43. Shored Mechanically Stabilized Earth Wall System
44. Traditional Compaction
45. Vacuum Preloading with and without Prefabricated Vertical Drains
46. Vibrocompaction
47. Vibro-Concrete Columns

The GeoTechTools.org web site is intended for use by:

- Public agency personnel at all levels
- Geotechnical, Structural, Civil, Pavement, and Bridge Engineers
- Project Managers, Procurement, Research, Maintenance, and District Engineers
- Consultants, General Contractors, Architect-Engineer groups
- Academics/Students

Some example uses of the site include:

- Learning about technologies
- Investigating candidate solutions
- Locating design & QC/QA methods
- Developing scoping cost estimates
- Developing specifications
- Locating additional information in references

It is also important to note that although the system was designed with a focus on transportation infrastructure in the U.S.A., the information has wide applicability to non-transportation projects and for projects outside the U.S.A.

The best way to become familiar with GeoTechTools.org is to go to the website, where registration is easy, and explore the many available options. Herein only a few screen shots are included as figures, to provide a brief overview.

The opening page of GeotechTools.org, shown in Figure 2, comes up after login to the website, and provides an overview of the system.

The page shown in Figure 3 contains a listing of all the technologies in the system. Clicking on any one technology of interest, for example Prefabricated Vertical Drains and Fill Preloading, brings up a screen providing links to the eight categories of information shown in Figure 1. A Technology Fact Sheet for this technology is shown in Figure 4. An example of a Column-Supported Embankment project case history is shown in Figure 5 and illustrates the general format used for documenting the case histories.

Technology-specific information on design, quality assurance and control, specifications, and costs is accessible by checking the appropriate boxes. Specific examples are also included for many of the technologies.

The interactive technology selection guidance part of GeoTechTools.org functions as follows. After agreeing to a disclaimer that you, the user, understand the limitations of the system and are responsible for whatever use you make of the results, you are directed to the page shown in Figure 6, where you select one of the four applications shown. If, for example, you choose Construction on Unstable Soils, then the screen shown in Figure 7 appears. You will note that several of the technologies in the list on the right of the screen have been grayed out because they are not applicable to the specified unstable soil condition. Then it is necessary to select among the options for the depth and thickness of the unstable soil condition. Successive screens and drop down menus ask more specific questions that lead to further refinement and reduction in the list of potentially applicable technologies. These questions and choices cover such things as purpose of improvement, project type, area of ground to be improved, depth to groundwater, site constraints, unusual soils, etc.

Once responses to these questions have been entered, the list of potentially suitable technologies will have been narrowed to two or three, and the relevant results can be summarized in a PDF file. At that point it is up to the user to make further studies and decisions appropriate for the project. This can be facilitated by reference to the detailed information available in the eight categories listed in Figures 2 and 3.

As GeoTechTools.org is a living system, the user can refer to a list of Frequently Asked Questions, submit comments and contribute additional information for consideration in continuing updates.

In conclusion of Part I of this paper, GeoTechTools.org provides a new resource for obtaining up-to-date information on ground improvement technologies in one place, enables selection and evaluation of methods potentially suitable for a specific project, and provides several additional benefits, including:

- Information that has been vetted and distilled is provided
- Better informed decisions are possible
- Project constraints can be addressed
- Mitigation of risks and claims can be reduced
- Innovations can be introduced
- Improved quality is possible
- Preliminary cost estimating is possible.

PART II: Sustainability Considerations in Ground Improvement

Sustainable development is a process by which a sustainable society that is able to continue indefinitely without depleting the earth and its resources is achieved (Parkin 2000 and Shillaber et al. 2015a). Sustainability considerations have become increasingly important when undertaking new projects, rehabilitating old infrastructure, mitigating risks from natural hazards, in environmental protection and enhancement, and for developing new resources.

Overall sustainability is considered to involve three considerations: protection and enhancement of the environment, minimizing costs, and maximizing societal benefits (Shillaber et al 2015a). Conceptually, the highest level of sustainability is considered to have been achieved when the three components are optimized to put a project in the central zone of the diagram in Figure 8. Quantifying these three components and assigning their relative importance for a major project is subjective and dependent on value judgments. Most often this will be done during the initial planning stage of a project. Therefore, from a ground improvement standpoint, the primary sustainability concern will be to minimize adverse environmental impacts.

Evaluation of the potentially adverse environmental impacts of a ground improvement project can be done by estimating and calculating the energy consumption and greenhouse gas (GHG) emissions associated with the materials, construction activities and subsequent operations

(Shillaber, et al., 2015b). Energy consumption provides a measure of resource depletion and GHG emissions are known to contribute to global warming and climate change.

To date, however, little attention has been directed at these sustainability measures in ground improvement projects. Current practice is usually to select materials, designs, and construction methods to meet project performance requirements at lowest cost. Since minimum performance requirements must be met by all acceptable designs, cost is often the deciding factor between alternative designs and construction methods.

Life Cycle Analysis (LCA) is used to calculate the Embodied Energy (EE) and CO_2 emissions. The embodied energy is all the energy consumed to bring an item to its present state. CO_2 is taken as a reference GHG; other GHGs are often converted into an equivalent quantity of CO_2 based on their warming potential.

For a ground improvement project, the LCA analysis extends from raw material extraction to completion of construction. Operational phases usually are not significant unless the ground improvement component requires lifetime operations, such as pumping, etc. There are three parts of the analysis (Shillaber, et al., 2015a): materials, transportation, and site operations, related as shown in Figure 9.

The EE and GHG values used in the LCA are obtained by multiplying construction material and operational quantities by unit coefficients for energy and emissions for each of the materials and operations and summing the results. Thus, the procedure is simple in concept but can be very detailed and lengthy in practice.

Embodied energy and CO_2 emissions coefficients for some construction materials are given in Table 3. More comprehensive lists are available in the literature, such as the Inventory of Carbon and Energy (Hammond and Jones, 2011a, 2011b) and others. Two models for carrying out the LCA that are useful for ground improvement projects are:

1. European Federation of Foundation Contractors – Deep Foundations Institute (EFFC-DFI), **Geotechnical Carbon Calculator**, which calculates only the CO_2 emission quantities (Carbone 4, 2014).
2. The Virginia Tech (VT) **SEEAM** (Streamlined Energy and Emissions Assessment Model), which calculates both the energy and CO_2. (Shillaber, et al., 2015b).

The results of the LCA can be used to compare the energy and emissions associated with alternative ground improvement methods for a project. They can also be used to provide an assessment of environmental impacts resulting from the ground improvement phase that contribute to an environmental evaluation of the entire project. These considerations, along with performance and cost, become useful in optimizing the design and selection of materials and methods to help improve overall sustainability.

LPV 111 - An illustrative case history.

LPV 111, an 8.5 km long flood protection levee in New Orleans, Louisiana, shown in Figure 10, was the largest application of Deep Soil Mixing (DSM) in the U.S.A. at the time of its completion This project, with a contract amount of about $350 million, involved raising an existing levee crest by about 3m to provide 100 year flood protection. Traditional earth fill levees could not be used because the flat slopes of the berms required for stability above a soft and weak clay foundation soil would encroach on adjacent protected land (Cali et al., 2012).

Alternative designs included (1) Prefabricated Vertical Drains (PVDs) to pre-consolidate the soft foundation soils and (2) a reinforced concrete T-wall (Cali et al., 2012). A SEEAM analysis was made for each of these alternatives. Typical elevation and plan views of the DSM supported earthen levee are shown in Figure 11. The levee profile for the PVD design is shown in Figure 12, and the reinforced concrete T-wall cross-section is shown in Figure 13.

The results of the SEEAM life-cycle analysis for the three designs are shown in Table 4. These results show that the T-Wall would be the most expensive, contain the most embodied energy, and produce the most emissions, based only on the materials required for construction. It was also deemed not suitable for possible ship impact loading in the adjacent navigable channel (URS Group, 2008). The PVD design would have the lowest estimated cost and smallest energy and emissions, but the construction time would have been too long for the time constraint placed on the project. The DSM design resulted in slightly higher estimated cost than the PVD design, and somewhat more embodied energy and emissions. However, the construction could be completed within the time constraint. Accordingly, it became the best option overall. Additional details regarding this case history and the analyses are presented by Shillaber et al., 2015(b).

Data for this same project also show that choices among materials and construction methods within a particular ground improvement technology can make a difference for sustainability. The improvement of 1.4 million cubic meters of foundation soil at LPV 111 required 417,000 tonnes of binder, 454,000 m^3 of water, and more than 3.9 million liters of diesel fuel (Shillaber et al., 2015c). The binder used was a mix of 75 percent slag and 25 percent Portland cement. The DSM spoils were incorporated into the embankment rather than wasted (Schmutzler et al., 2012; Druss et al., 2012).

The EE and CO_2 quantities for these materials and operations were compared with values for 100 percent Portland cement binder and for transporting the spoil offsite for disposal. The results are given in Table 5 and Figure 14 for embodied energy and Table 6 and Figure 15 for CO_2 emissions. The proportional contributions of materials, material transportation, site operations and waste transportation for each condition are shown for embodied energy in Figure 16 and for CO_2 emissions in Figure 17.

Collectively these results show that binder material differences can have a very significant impact on the resulting embodied energy and emissions. If 100% Portland cement were used, the embodied energy and emissions would have been much greater. If the DSM spoil had not been recycled into the levee embankment on-site, the embodied energy and emissions would have increased, but not nearly as much as the difference between the cement-slag binder and 100 percent Portland cement binder.

There are ancillary sustainability benefits of reusing waste material on site, some of which are of economic and societal value (see Figure 8), as noted by Shillaber, et al. (2015c). Landfill and other disposal facility space is saved, a societal benefit. Disposal costs for waste materials are reduced, an economic benefit. Less transportation of waste on roads reduces traffic, road wear and tear, etc., which are societal and economic benefits. Replacing clay borrow with spoil reduces borrowing additional material, and this saves on excavation, transportation, and disposal of the DSM spoil, which are societal and economic benefits.

In conclusion of Part II of this paper: Embodied Energy and CO_2 emissions are indicators of environmental impact. Quantified values of EE and CO_2 emissions can be used to aid in selection and refinement of ground improvement technologies and designs for sustainable development.

CONCLUDING COMMENTS

GeoTechTools.org is a readily available and easily accessed online source of information about many ground improvement methods and their applications, design, construction, costs, and performance. It can also be used for guidance in the selection of suitable methods for particular projects.

From the ground improvement technology selected, to the finer aspects of its design and construction (such as binder/material types and construction time), the decisions we make as geotechnical engineers can significantly influence not only the cost and performance of a project, but also the environment. All three of these factors should be considered if we are to make sound decisions for more sustainable development.

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Table 1. *Categories, Functions and Methods of Ground Improvement.*

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, geotextile-encased columns, sand compaction piles, jet grouted columns, etc.)
		Reinforced embankments
Chemical Treatment	Increase density, increase compressive and tensile strength, fill voids, form seepage cutoffs	Chemical admixtures
		Cement and chemical grouting
		Fracture grouting
		Lime columns
Thermal stabilization	Increase shear strength, provide cutoffs	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

Table 2. *Input and output items needed for analysis and design of a ground improvement project.*

Categories of Input and Output Items for Analysis and Design Procedures	**Some Example Items**
Performance Criteria/Indicators	Minimum factor of safety, load and resistance factors, allowable settlements and 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 and structure loads, embankment pressure, earthquake acceleration and duration, water pressures
Material Characteristics	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
Geometry	Diameter, spacing, depth, thickness, length, area, slope

Table 3. *Embodied Energy and Carbon Coefficients for some construction materials* (adapted from Shillaber et al., 2015b).

Material Category	Material	EE Coefficient (MJ/Unit)	CO_2 Coefficient (kg CO_2/Unit)	Unit	Reference
Steel	General Steel, Virgin	35.4	2.71	kg	Hammond and Jones (2011b)
	General Steel, World Avg. Recycled Content	25.3	1.82	kg	Hammond and Jones (2011b)
	Steel Bar and Rod, Virgin	29.2	2.59	kg	Hammond and Jones (2011b)
	Steel Bar and Rod, World Avg. Recycled Content	21.6	1.74	kg	Hammond and Jones (2011b)
	Engineered Sections, Virgin	38.0	2.82	kg	Hammond and Jones (2011b)
	Engineered Sections, World Avg. Recycled Content	27.1	1.89	kg	Hammond and Jones (2011b)
Cementitious Materials	Portland Cement (U.S.)	4.798	0.927	kg	Marceau et al. (2006)
	Lime	5.3	0.76	kg	Hammond and Jones (2011b)
	Slag (U.S.)	0.721	0.021	kg	Slag Cement Association (n.d.)
	Fly Ash	0.1	0.008	kg	Hammond and Jones (2011b)
Concrete	35MPa Concrete (Portland Cement Only)	1,630	313	m^3	Marceau et al. (2007)
	25MPa Concrete (Portland Cement Only)	1,390	262	m^3	Marceau et al. (2007)
	20MPa Concrete (Portland Cement Only)	1,140	211	m^3	Marceau et al. (2007)
	20MPa Concrete (20% Fly Ash by Weight)	944	171	m^3	Marceau et al. (2007)
Earth Material	Aggregate: Sand and Gravel or Crushed Rock	0.083	0.0048	kg	Hammond and Jones (2011b)
	Bentonite	1.65	0.101	kg	Jiang et al. (2011); Carnegie Mellon University (2008)
Plastics	General Plastics (Average)	80.5	2.73	kg	Hammond and Jones (2011b)
	Polyethylene (General)	83.1	2.04	kg	Hammond and Jones (2011b)
	Polypropylene (Injection Molding)	115.1	3.93	kg	Hammond and Jones (2011b)
	Polypropylene (Oriented Film)	99.2	2.97	kg	Hammond and Jones (2011b)
Water	Water	0.01	0.001	L	Hammond and Jones (2011b)
Fuel	Diesel	42.967	3.248	L	Shillaber et al. (2014)
	Gasoline	39.658	2.826	L	Shillaber et al. (2014)
	Compressed Natural Gas (CNG)	55.462	2.87	kg	Shillaber et al. (2014)
	Electricity (U.S. Avg. Generation Mix)	8.736	0.627	kW-hr	Shillaber et al. (2014)

Table 4. *Comparison of LPV 111 design alternatives using SEEAM Life Cycle Analyses* (adapted from Shillaber et al., 2015b).

	Deep Soil Mixing	**Prefabricated Vertical Drains**	**Pile Supported Concrete T-Wall**
Embodied Energy (GJ)	1,174,000	812,000	2,755,000
CO_2 Emissions (tonnes)	147,000	64,000	211,000
Estimated Cost (USD) (URS Group, 2008)	$ 372,800,000	$ 361,000,000	$ 546,600,000
Comment(s)	-As built final design -Constructed in 14 months	-Construction time projected to exceed 20 month limit	-EE and CO_2 results account for materials only -T-wall not suited for ship impact loading

Table 5. *Comparison of LPV 111 Embodied Energy values as built with those for use of 100% Portland cement binder and for no DSM spoil recycling* (adapted from Shillaber et al., 2015c).

	Materials	**Materials Transport**	**Site Operations**	**Waste Transport**	**TOTAL**	**Normalized EE**[a]
As Built (GJ)	762,000	151,000	261,000	0	**1,174,000**	**1.00**
100% Portland Cement Binder (GJ)	2,037,000	127,000	261,000	0	**2,425,000**	**2.07**
No DSM Spoil Recycling (GJ)	762,000	197,000	269,000	50,000	**1,278,000**	**1.09**

[a]Normalized EE is the ratio of the design alternative EE to the As-Built EE.

Table 6. *Comparison of LPV 111 CO_2 emission values as built with those for use of 100% Portland cement binder and for no DSM spoil recycling* (adapted from Shillaber et al., 2015c).

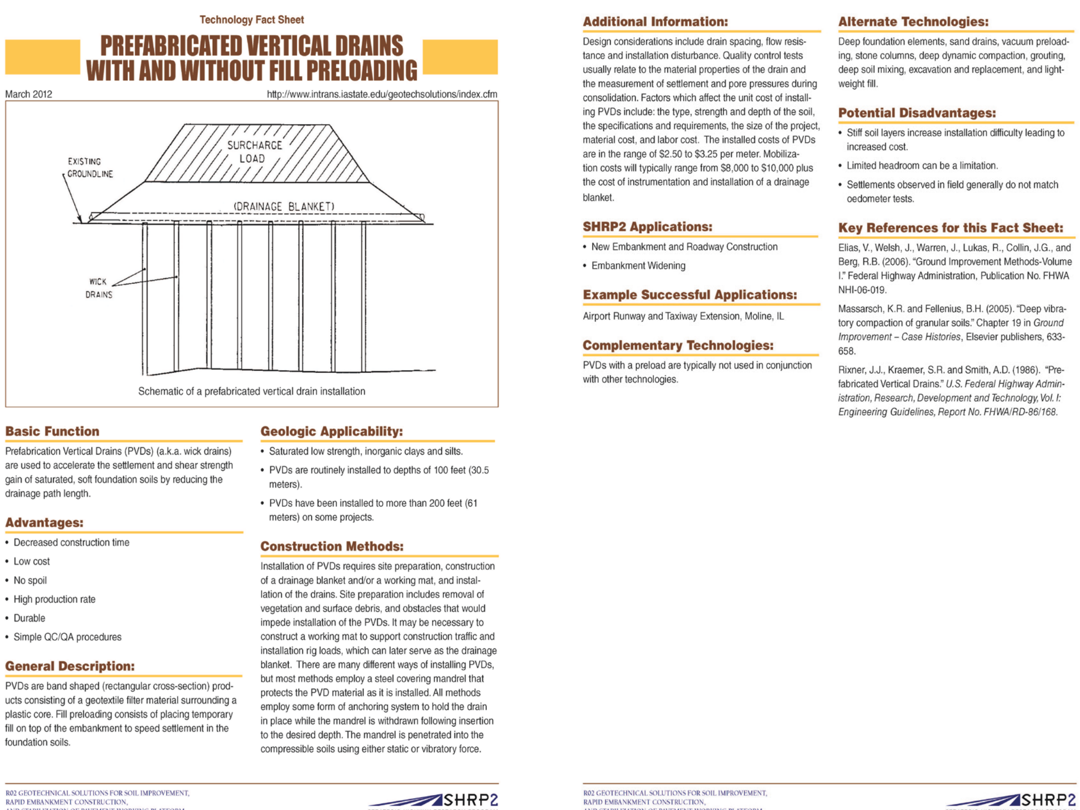
	Materials	**Materials Transport**	**Site Operations**	**Waste Transport**	**TOTAL**	**Normalized CO_2[a]**
As Built (tonnes CO_2)	105,000	22,000	20,000	0	**147,000**	**1.00**
100% Portland Cement Binder (tonnes CO_2)	388,000	18,000	20,000	0	**426,000**	**2.90**
No DSM Spoil Recycling (tonnes CO_2)	105,000	26,000	20,000	4,000	**155,000**	**1.05**

[a]Normalized CO_2 is the ratio of the design alternative CO_2 to the As-Built CO_2.

Figure 1. *The eight categories of information for each technology included in the* GeoTechTools.org *website "tool box."*

Figure 2. *Opening page of* GeoTechTools.org. *Links to various components of the system are listed in the left column.*

Figure 3. *All technologies are listed alphabetically in the right column. They are also listed within one of 11 application classification categories.*



Technology Fact Sheet

PREFABRICATED VERTICAL DRAINS WITH AND WITHOUT FILL PRELOADING

March 2012 http://www.intrans.iastate.edu/geotechsolutions/index.cfm

Schematic of a prefabricated vertical drain installation

Basic Function

Prefabrication Vertical Drains (PVDs) (a.k.a. wick drains) are used to accelerate the settlement and shear strength gain of saturated, soft foundation soils by reducing the drainage path length.

Advantages:

- Decreased construction time
- Low cost
- No spoil
- High production rate
- Durable
- Simple QC/QA procedures

General Description:

PVDs are band shaped (rectangular cross-section) products consisting of a geotextile filter material surrounding a plastic core. Fill preloading consists of placing temporary fill on top of the embankment to speed settlement in the foundation soils.

Geologic Applicability:

- Saturated low strength, inorganic clays and silts.
- PVDs are routinely installed to depths of 100 feet (30.5 meters).
- PVDs have been installed to more than 200 feet (61 meters) on some projects.

Construction Methods:

Installation of PVDs requires site preparation, construction of a drainage blanket and/or a working mat, and installation of the drains. Site preparation includes removal of vegetation and surface debris, and obstacles that would impede installation of the PVDs. It may be necessary to construct a working mat to support construction traffic and installation rig loads, which can later serve as the drainage blanket. There are many different ways of installing PVDs, but most methods employ a steel covering mandrel that protects the PVD material as it is installed. All methods employ some form of anchoring system to hold the drain in place while the mandrel is withdrawn following insertion to the desired depth. The mandrel is penetrated into the compressible soils using either static or vibratory force.

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Additional Information:

Design considerations include drain spacing, flow resistance and installation disturbance. Quality control tests usually relate to the material properties of the drain and the measurement of settlement and pore pressures during consolidation. Factors which affect the unit cost of installing PVDs include: the type, strength and depth of the soil, the specifications and requirements, the size of the project, material cost, and labor cost. The installed costs of PVDs are in the range of $2.50 to $3.25 per meter. Mobilization costs will typically range from $8,000 to $10,000 plus the cost of instrumentation and installation of a drainage blanket.

SHRP2 Applications:

- New Embankment and Roadway Construction
- Embankment Widening

Example Successful Applications:

Airport Runway and Taxiway Extension, Moline, IL

Complementary Technologies:

PVDs with a preload are typically not used in conjunction with other technologies.

Alternate Technologies:

Deep foundation elements, sand drains, vacuum preloading, stone columns, deep dynamic compaction, grouting, deep soil mixing, excavation and replacement, and lightweight fill.

Potential Disadvantages:

- Stiff soil layers increase installation difficulty leading to increased cost.
- Limited headroom can be a limitation.
- Settlements observed in field generally do not match oedometer tests.

Key References for this Fact Sheet:

Elias, V., Welsh, J., Warren, J., Lukas, R., Collin, J.G., and Berg, R.B. (2006). "Ground Improvement Methods-Volume I." Federal Highway Administration, Publication No. FHWA NHI-06-019.

Massarsch, K.R. and Fellenius, B.H. (2005). "Deep vibratory compaction of granular soils." Chapter 19 in *Ground Improvement – Case Histories*, Elsevier publishers, 633-658.

Rixner, J.J., Kraemer, S.R. and Smith, A.D. (1986). "Prefabricated Vertical Drains." *U.S. Federal Highway Administration, Research, Development and Technology, Vol. I: Engineering Guidelines, Report No. FHWA/RD-86/168.*

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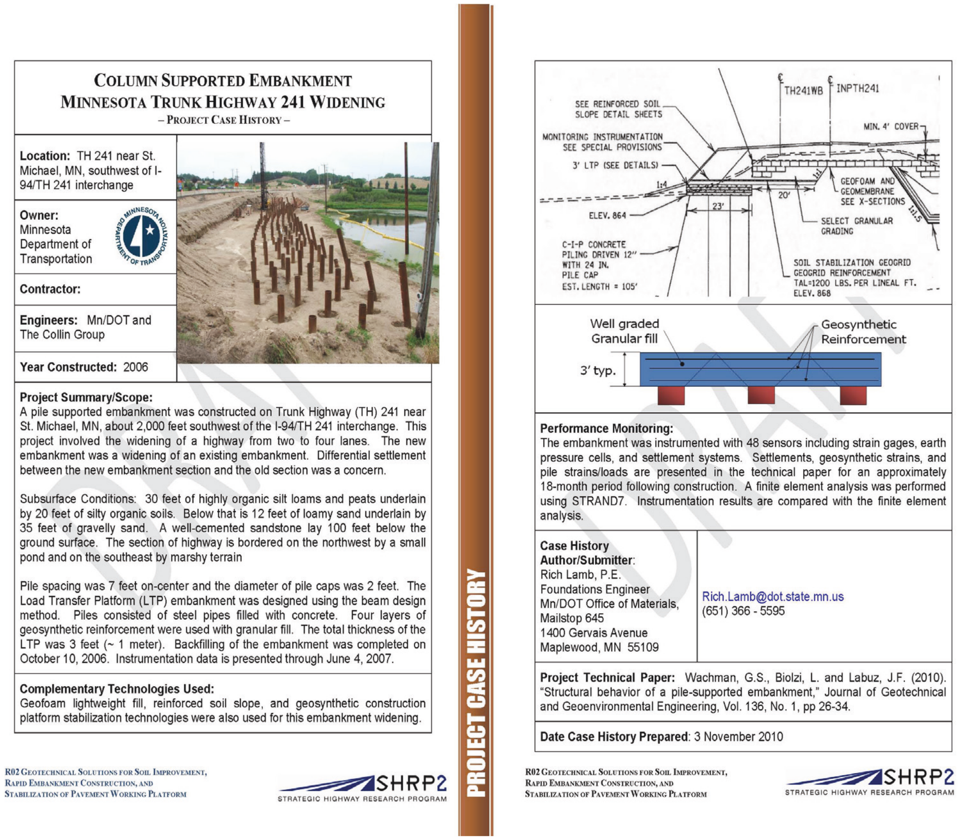
Figure 4. *Technology Fact Sheet for Prefabricated Vertical Drains With and Without Fill Preloading.*



COLUMN SUPPORTED EMBANKMENT
MINNESOTA TRUNK HIGHWAY 241 WIDENING
– PROJECT CASE HISTORY –

Location: TH 241 near St. Michael, MN, southwest of I-94/TH 241 interchange

Owner: Minnesota Department of Transportation

Contractor:

Engineers: Mn/DOT and The Collin Group

Year Constructed: 2006

Project Summary/Scope:
A pile supported embankment was constructed on Trunk Highway (TH) 241 near St. Michael, MN, about 2,000 feet southwest of the I-94/TH 241 interchange. This project involved the widening of a highway from two to four lanes. The new embankment was a widening of an existing embankment. Differential settlement between the new embankment section and the old section was a concern.

Subsurface Conditions: 30 feet of highly organic silt loams and peats underlain by 20 feet of silty organic soils. Below that is 12 feet of loamy sand underlain by 35 feet of gravelly sand. A well-cemented sandstone lay 100 feet below the ground surface. The section of highway is bordered on the northwest by a small pond and on the southeast by marshy terrain

Pile spacing was 7 feet on-center and the diameter of pile caps was 2 feet. The Load Transfer Platform (LTP) embankment was designed using the beam design method. Piles consisted of steel pipes filled with concrete. Four layers of geosynthetic reinforcement were used with granular fill. The total thickness of the LTP was 3 feet (~ 1 meter). Backfilling of the embankment was completed on October 10, 2006. Instrumentation data is presented through June 4, 2007.

Complementary Technologies Used:
Geofoam lightweight fill, reinforced soil slope, and geosynthetic construction platform stabilization technologies were also used for this embankment widening.

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PROJECT CASE HISTORY

SEE REINFORCED SOIL SLOPE DETAIL SHEETS
MONITORING INSTRUMENTATION SEE SPECIAL PROVISIONS
3' LTP (SEE DETAILS)
ELEV. 864
C-I-P CONCRETE PILING DRIVEN 12" WITH 24 IN. PILE CAP EST. LENGTH = 105'
TH241WB
INPTH241
MIN. 4' COVER
GEOFOAM AND GEOMEMBRANE SEE X-SECTIONS
SELECT GRANULAR GRADING
SOIL STABILIZATION GEOGRID GEOGRID REINFORCEMENT TAL=1200 LBS. PER LINEAL FT. ELEV. 868

Well graded Granular fill
Geosynthetic Reinforcement
3' typ.

Performance Monitoring:
The embankment was instrumented with 48 sensors including strain gages, earth pressure cells, and settlement systems. Settlements, geosynthetic strains, and pile strains/loads are presented in the technical paper for an approximately 18-month period following construction. A finite element analysis was performed using STRAND7. Instrumentation results are compared with the finite element analysis.

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Project Technical Paper: Wachman, G.S., Biolzi, L. and Labuz, J.F. (2010). "Structural behavior of a pile-supported embankment," Journal of Geotechnical and Geoenvironmental Engineering, Vol. 136, No. 1, pp 26-34.

Date Case History Prepared: 3 November 2010

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Figure 5. *An example Project Case History: Column Supported Embankment - Minnesota Trunk Highway 241 Widening.*

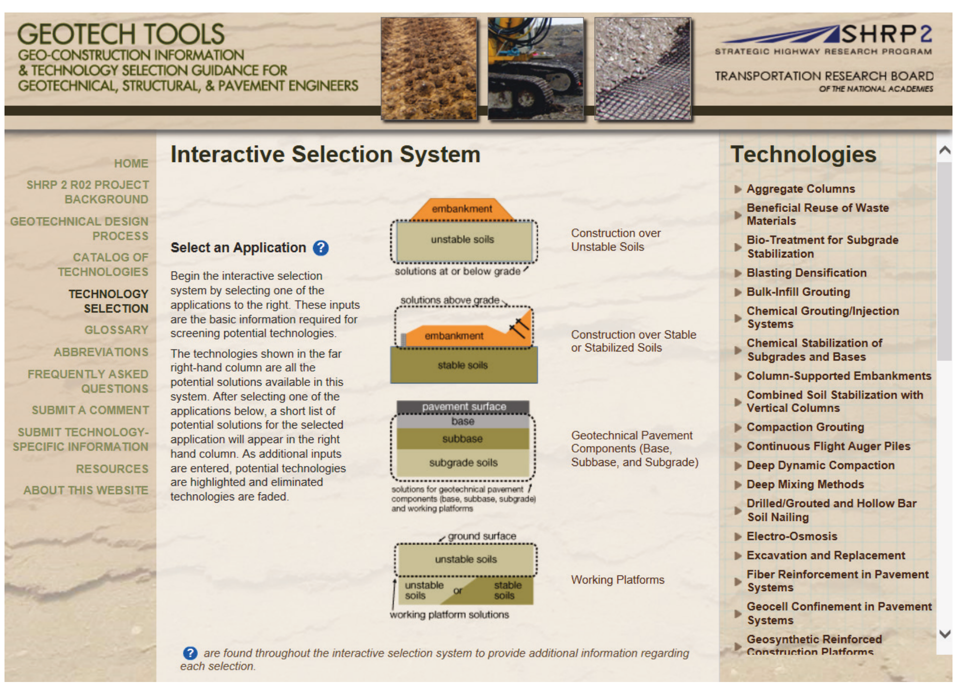

Figure 6. *The first step in using the interactive selection system is to select one of the four applications shown on this screen.*

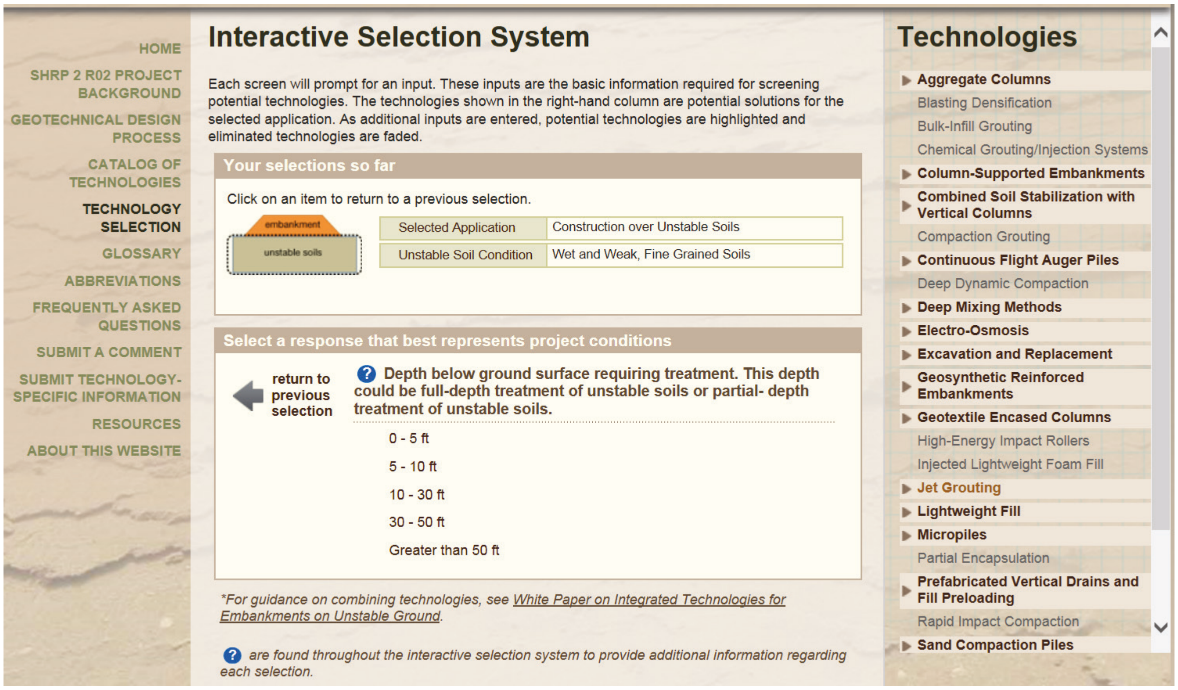

Figure 7. *Responses to successive questions on subsequent screens further define the problem and limit the potentially applicable technologies as indicated by the graying out of some of them in the right column.*

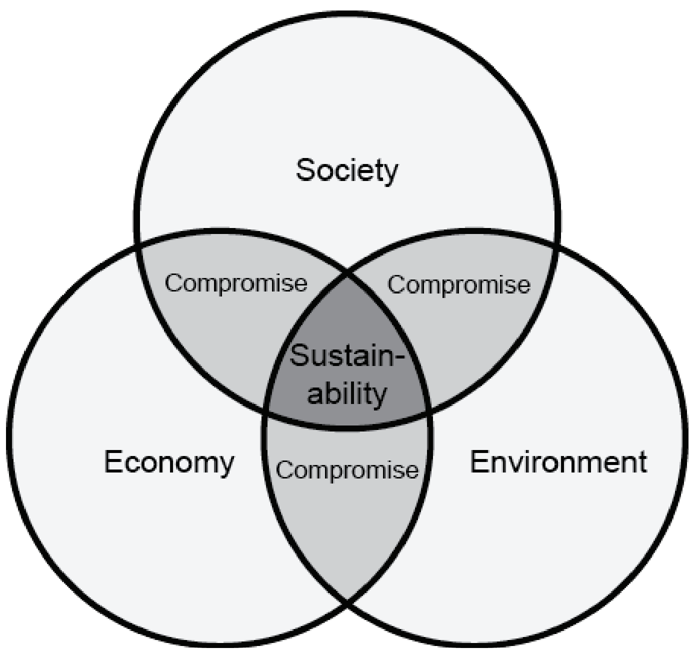

Figure 8. *The three components of sustainability. Maximizing the overlap of Environmental, Economic and Societal benefits leads to the most sustainable designs* (adapted from Shillaber et al. 2015a).

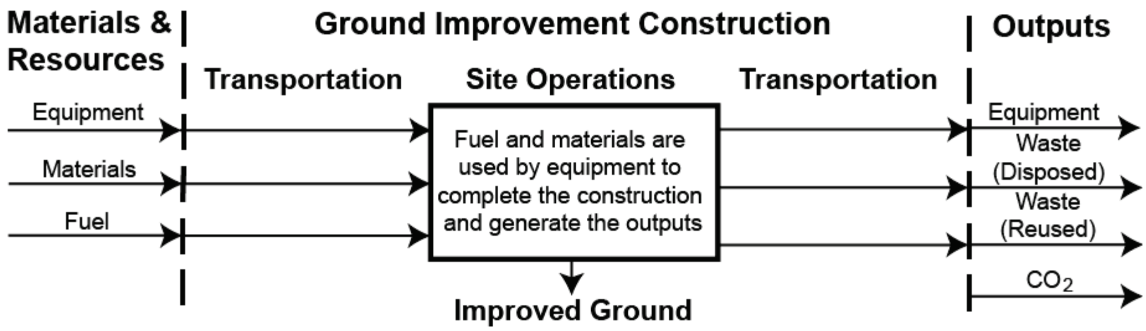

Figure 9. *Life Cycle Analysis (LCA) for a ground improvement project usually extends from raw material extraction to completion of construction and requires consideration of materials, transportation and site operations* (adapted from Shillaber et al. 2015b).

Figure 10. Levee *LPV 111 in New Orleans, Louisiana. An illustrative case history for evaluation of sustainability considerations in ground improvement.* (U.S. Army Corps of Engineers Photograph)

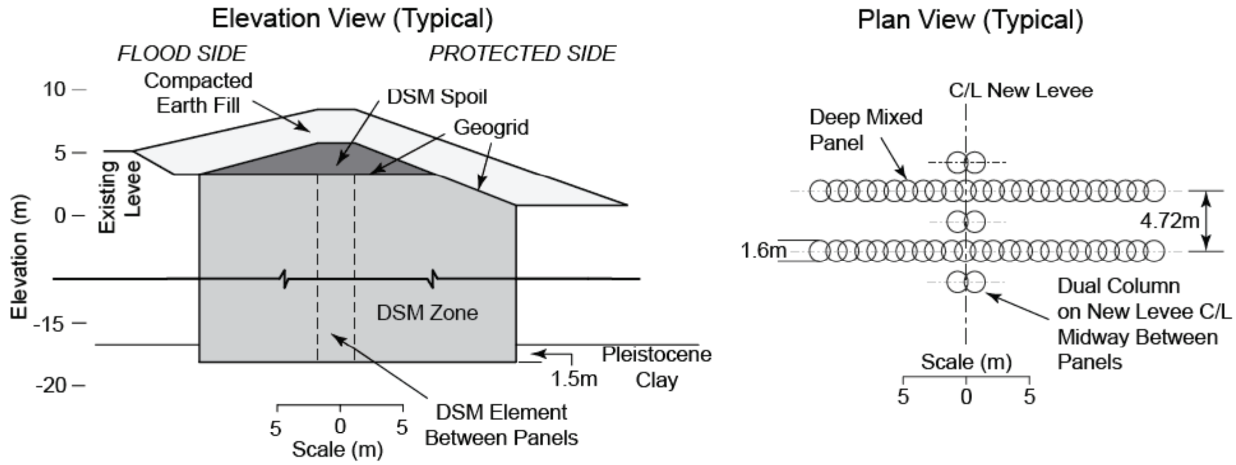

Figure 11. *Typical elevation and plan views of the Deep Soil Mixing zone at LPV 111* (adapted from Cooling et al., 2012).

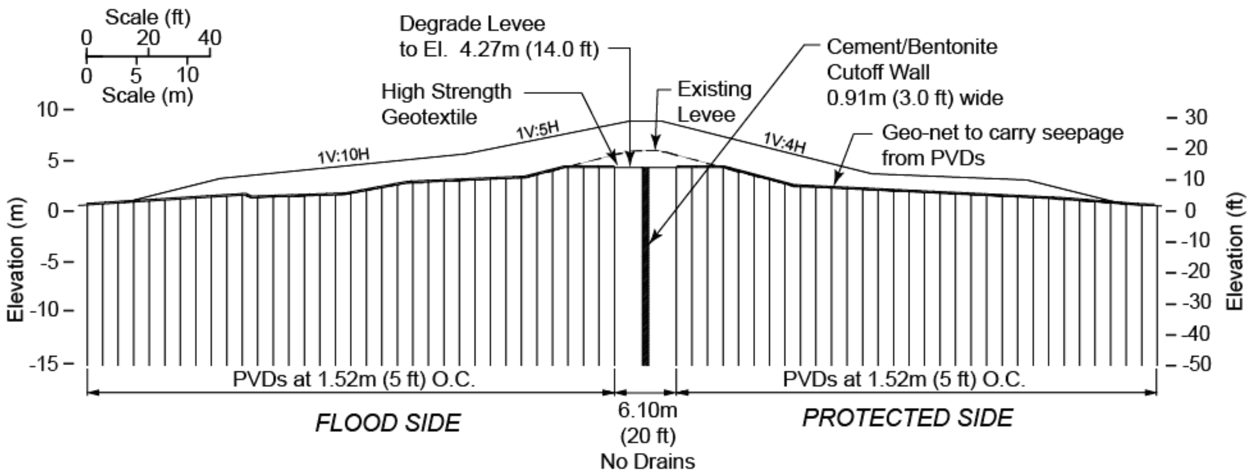

Figure 12. *Typical LPV 111 levee profile for the Prefabricated Vertical Drain (PVD) design* (adapted from URS Group, 2008).

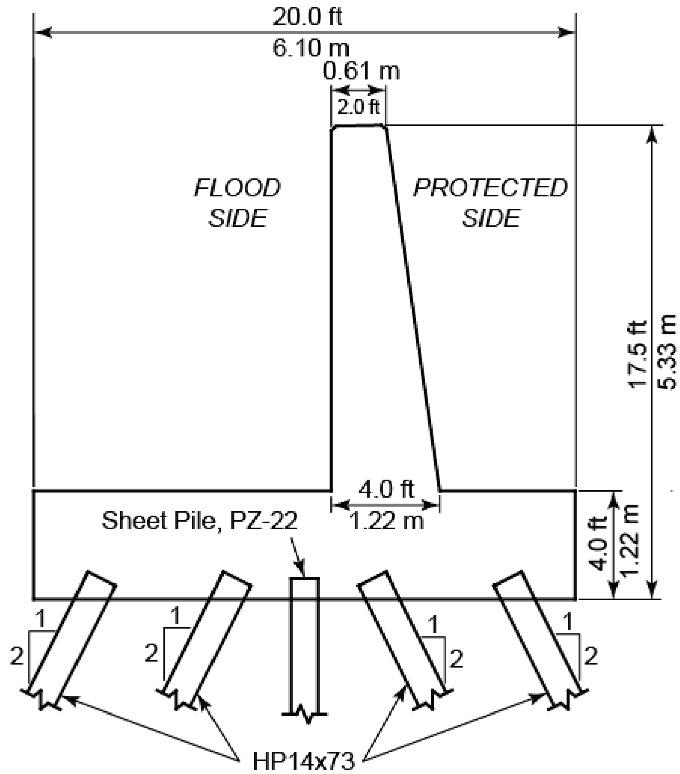

Figure 13. *Typical LPV 111 levee profile for the Reinforced Concrete T-Wall* (adapted from URS Group, 2008).

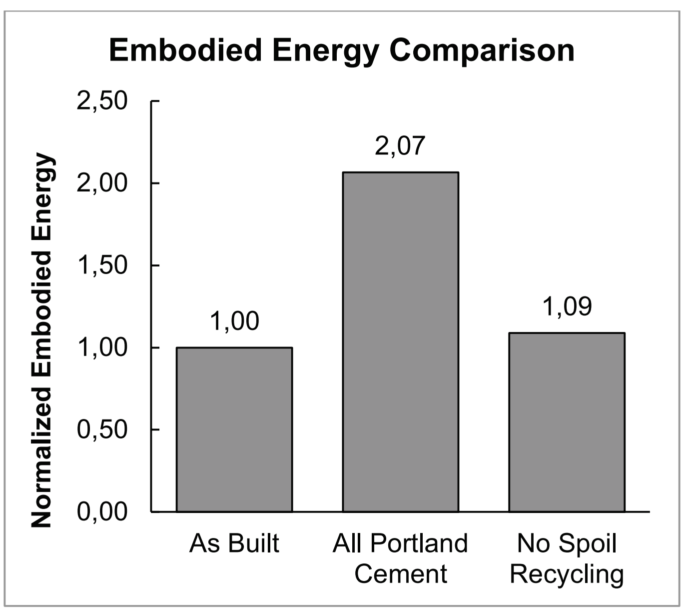

Figure 14. *Comparison of the normalized embodied energies for the LPV 111 project as built, with those for 100% Portland cement binder and no DSM spoil recycling* (adapted from Shillaber et al., 2015c).

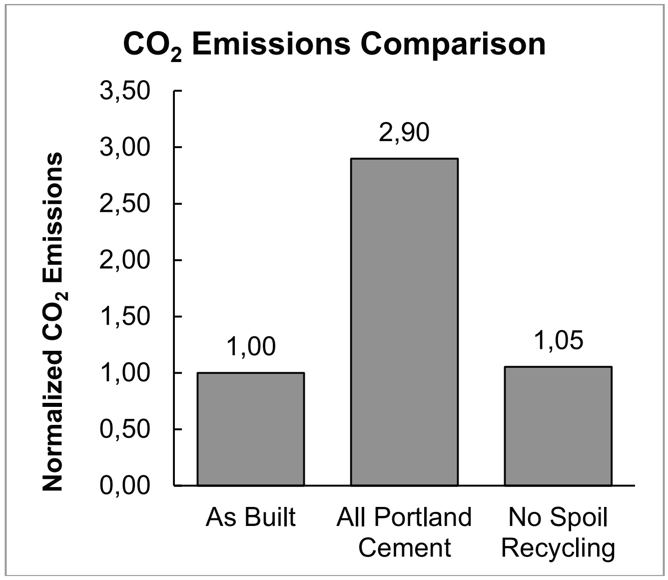

Figure 15. *Comparison of the normalized CO_2 emissions for the LPV 111 project as built, with those for 100% Portland cement binder and for no DSM spoil recycling* (adapted from Shillaber et al., 2015c).

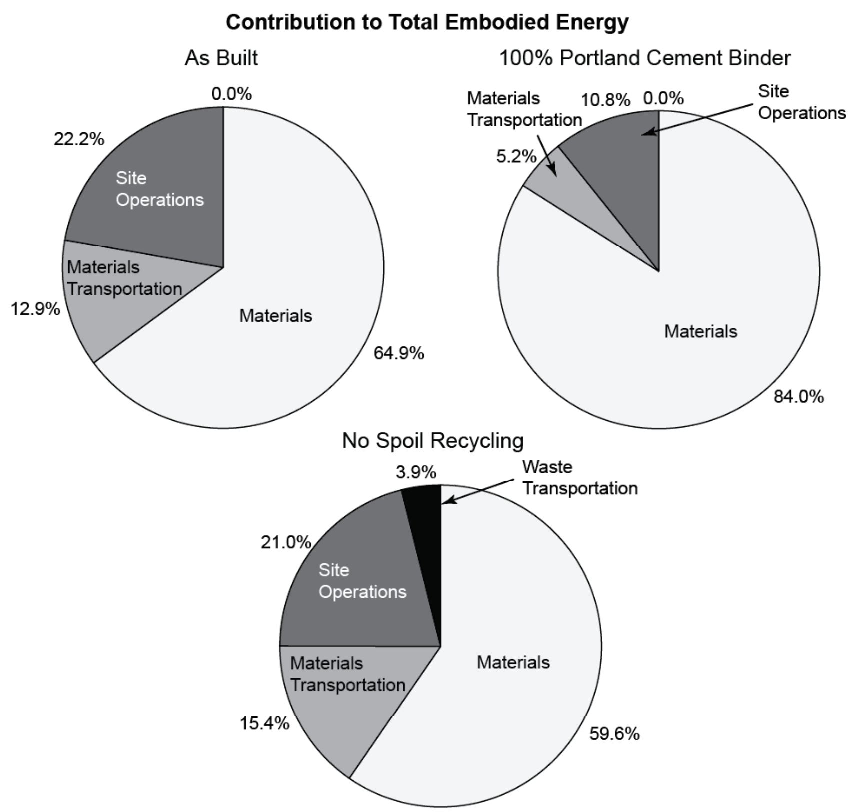

Figure 16. *Comparison of the contributions to the total embodied energy for the LPV 111 binder as built with those for 100% Portland cement binder and for no DSM spoil recycling* (adapted from Shillaber et al., 2015c).

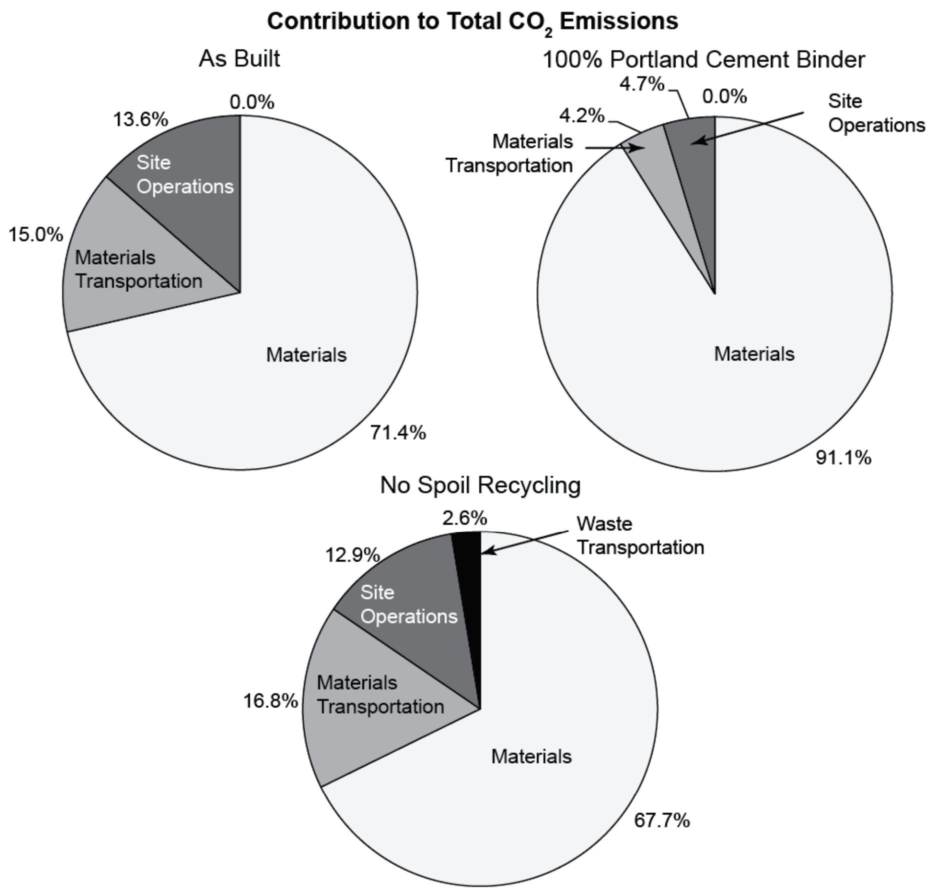

Figure 17. *Comparison of the contributions to the total CO_2 emissions for the LPV 111 binder as built with those for 100% Portland cement binder and for no DSM spoil recycling* (adapted from Shillaber et al., 2015c).

Laurits Bjerrums Minnefond

Statutter

§ 1 Opprettelse

Laurits Bjerrums minnefond er opprettet av Norsk geoteknisk forening, dels ved egne midler, og dels ved gaver fra private firmaer og offentlige institusjoner, samt fra enkeltpersoner.

§ 2 Formål

Fondets avkastning skal benyttes til å fremme geoteknisk forskning og stimulere det geotekniske miljø ved følgende tiltak:

(a) Laurits Bjerrums ærespris tildeles for et fremragende enkeltarbeid, eller for flere betydelige arbeider som sammen har fremmet faget geoteknikk og fundamentering.

(b) Laurits Bjerrums stipendium benyttes fortrinnsvis til å stimulere yngre, lovende geoteknikere til forskning innen faget.

(c) Laurits Bjerrums minneforedrag holdes av fremstående geoteknikere som inviteres og honoreres.

§ 3 Styre

Fondets midler forvaltes av et styre på 3 medlemmer valgt av generalforsamlingen i Norsk geoteknisk forening for en periode på 5 år, med mulighet for gjenvalg av de enkelte styremedlemmer én gang. Norsk geoteknisk forenings sekretær, kasserer og revisor fungerer som sådanne også for fondsstyret. Fondsstyret skal holde minst ett møte pr. år. Sekretæren innkaller til møtene og deltar i disse.

Fondsstyret tar avgjørelser i alle saker som vedrører bruk av fondets avkastning til ovennevnte formål Resultatet av avgjørelsen meddeles til Norsk geoteknisk forening som skal være arrangør ved minneforedragene og ved utdeling av ærespris og stipendium.

§ 4 Anvendelsesprinsipp

Anvendelsen av fondets avkastning skal så vidt mulig skje i Laurits Bjerrums ånd. Regelmessighet og rutine ved utdelingen bør vike prioritet for originalitet og oppfinnsomhet. Det eksepsjonelle skal honoreres fremfor mengde, og ved de respektive seremonier og tilstelninger skal det legges vekt på å skape særpreg og festivitas.

§ 5 Statuttendringer

Bestemmelsene i disse statutter kan etter år 2000, endres av Norsk geoteknisk forening i henhold til foreningens egne statutter. Fondsstyret skal på forhånd enstemmig ha erklært seg enig i endringsforslaget.

Statutter vedtatt av Norsk geoteknisk forenings generalforsamling 18. september 1973