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The Charles E. Via, Jr. Department of Civil Engineering

CENTER FOR GEOTECHNICAL PRACTICE AND RESEARCH

White Paper on Integrated Technologies for Embankments on Unstable Ground

by

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CHAPTER 1

INTRODUCTION

1.1. BACKGROUND

1.1.1. SHRP 2 R02

Although in existence for several decades, many geoconstruction technologies face both technical and non-technical obstacles preventing broader utilization in transportation infrastructure projects. The research team for Strategic Highway Research Program 2, Project Number R02 (SHRP 2 R02) *Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform* is investigating the state of practices of transportation project engineering, geotechnical engineering, and earthwork construction to identify and assess methods to advance the use of geoconstruction technologies. Such technologies are often underutilized in current practice, and they offer significant potential to achieve one or more of the SHRP 2 Renewal objectives, which are rapid renewal of transportation facilities, minimal disruption of traffic, and production of long-lived facilities. Project R02 encompasses a broad spectrum of materials, processes, and technologies within geotechnical engineering and geoconstruction that are applicable to one or more of the following “elements” of construction (as defined in the project scope): (1) new embankment and roadway construction over unstable soils; (2) roadway and embankment widening; and (3) stabilization of pavement working platforms.

1.1.2. Information & Guidance System

An Information & Guidance System has been developed to provide a framework for applying the technologies, and is contained on the SHRP 2 R02 Geotechnical Solutions for Transportation Infrastructure website, www.GeoTechTools.org. The system will promote more widespread use of soil improvement technologies to achieve SHRP 2 Renewal objectives. This system provides the data necessary for determining the applicability of specific technologies to specific projects, and then guides the user to information needed to apply the selected technology. The Information & Guidance System will guide the user to one or more potential technologies. From these potential technologies, the user can access the catalog which includes information necessary for screening (i.e., depth limits, applicability to different soil types, acceptable groundwater conditions, applicability to different project types, ability to deal with project-specific constraints, general advantages/disadvantages, etc.), as well as design methodologies, quality assurance and control, costs, and specifications.

1.2. SCOPE

The Information & Guidance System has been developed to identify potential technologies to use for general project conditions. However, it does not identify where a combination of technologies should be considered. Such consideration is very project conditions/constraints-specific. Because of this, the engineer needs to identify how different technologies can be combined and where and when they can be combined.

This paper is provided as part of the Information & Guidance System to discuss the use of a combination of two or more ground improvement technologies for a single application and explain the potential benefits of these combinations. It includes possible combinations and the reasons these combinations are efficient based on soil and site parameters. It also includes case histories of the successful use of multiple technologies to stabilize soils under an embankment. This paper does not include design guidelines or procedures, quality control/quality assurance procedures, seismic design considerations or detailed information about specific ground improvement technologies (this can be obtained from the Information & Guidance System). This paper is intended for use in conjunction with the Information & Guidance System. However, if the Information & Guidance System is not available, summary fact sheets for the technologies discussed can be found in an appendix to this paper.

While this paper will give numerous possible and successful combinations, it does not give all the potential ground improvement technology combinations. The engineer should use this paper as a guide only and research other potentially useful combinations. The design of any ground improvement project and especially when combining two or more ground improvement techniques must consider both site and project specific constraints and objectives. The design should also consider constructability as this is often the key to a successful project.

1.3. ORGANIZATION

The first section of this paper discusses the different foundation treatment technologies that can be combined to improve unstable soils and the embankment construction technologies that can be used in conjunction with the foundation treatment technologies. A brief summary of each technology and its applications is provided with links to further information as stated above either in the Information & Guidance System or attached as an appendix to this paper.

The following section discusses the combinations of the technologies found in the literature review. The final section of the paper summarizes successful case history summaries for a number of the combinations, and provides references for additional case histories that were not summarized.

CHAPTER 2

EMBANKMENTS OVER UNSTABLE SOILS

2.1. TYPICAL PROJECTS

Generally, there are five typical types of projects that include embankments over unstable soils:

- bridge approach embankments over soft soils
- new embankments over deep soft soils
- new embankments over shallow soft soils
- widening of existing embankments over deep soft soils
- widening of existing embankments over shallow soft soils

Shallow soft soils are generally considered to extend to a depth where excavation and replacement techniques are commonly used. Deep soft soils are generally considered to extend to a depth where in situ stabilization techniques are used because the soils are too deep to effectively and efficiently excavate. Figure 1 shows an example of a new column supported embankment used to stabilize deep soft soils and Figure 2 is an example of an embankment over shallow soft soils.

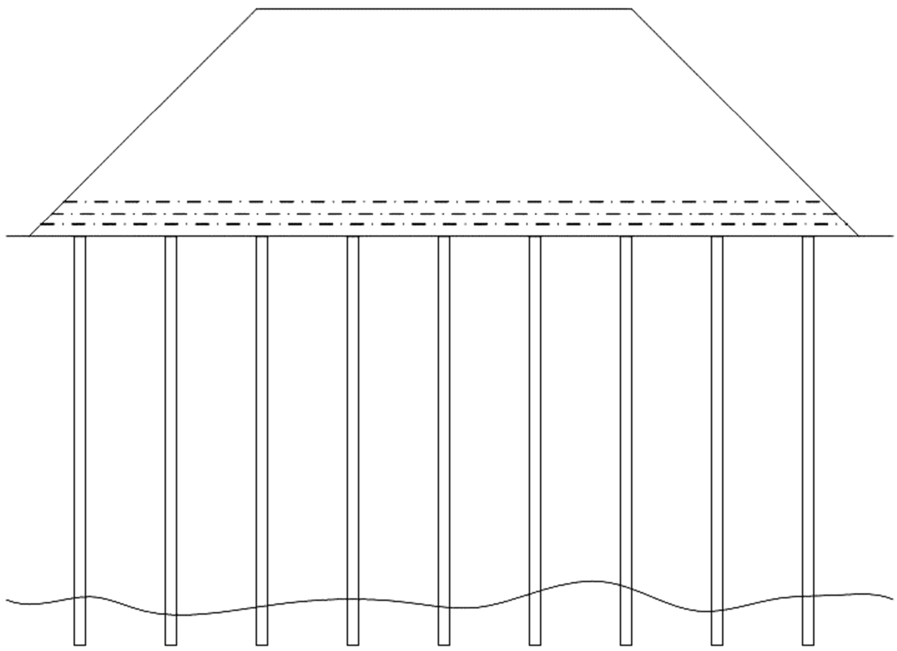

Figure 1. Column supported embankment used to stabilize deep soft soils

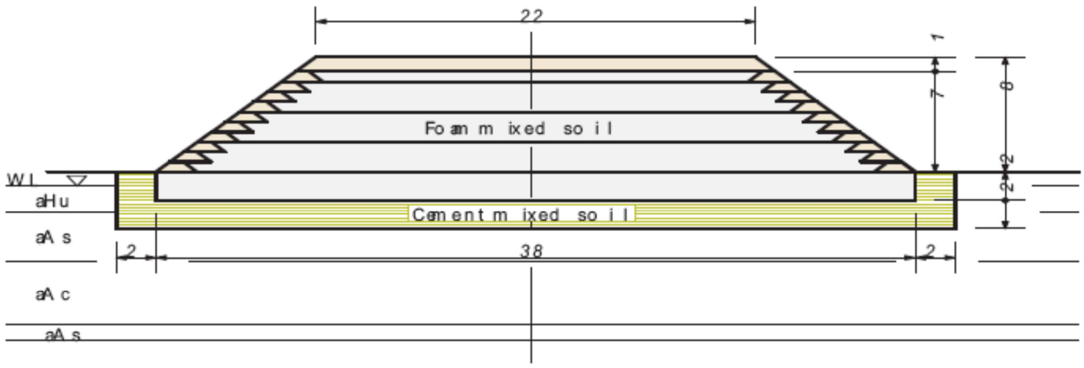

Figure 2. Embankment over shallow soft soils from Miki (2005).

2.2. Design Considerations

Although the ground improvement technologies discussed in this paper may not always be the most cost efficient, there are numerous reasons why they may be used. They include issues with stability both during and after construction, the need for accelerated construction and reduction of post-construction settlement. For example, rather than removing soft soils or using prefabricated vertical drains with fill preloading, load-carrying lightweight fill may be installed because of a tight construction schedule. Other design or construction challenges include a reduced embankment width due to limited right-of-ways. This problem may require a column supported embankment rather than a traditional embankment. In addition, to get the biggest advantage with respect to time or stability, two or more combinations of ground improvement technologies may be used. This may entail the use of a type of column such as deep mixing methods columns with technology such as prefabricated vertical drains with fill preloading to accelerate the construction schedule. This paper will discuss a number of these combinations and several case histories. These summaries provide examples of how different technologies have been combined and the advantages gained from these combinations.

2.3. Foundation Treatment Technologies

Table 1 shows the technologies that generally can be used with different soil types. A short description is provided for each technology and further information can be found in the Information & Guidance System.

Table 1. Foundation Soil Treatment Technologies for Embankment Construction

Foundation Soil Condition	Foundation Soil Treatment Technologies
Soft Clay	Excavation and Replacement PVDs with Fill Preloading Vacuum Preloading with and without PVDs Various Types of Columns 1. sand compaction columns 2. aggregate columns 3. rammed aggregate piers 4. VCCs 5. CFA piles 6. geotextile encased columns 7. CSV soil stabilization system Load Transfer Platforms Construction Platforms Deep Mixing Methods
Loose Sand (freely draining cohesionless soils)	Vibrocompaction Deep Dynamic Compaction Rapid Impact Compaction High Energy Impact Rollers Blast Densification Various Types of Columns (see above)
Soft/Loose Silt	See the discussion below for appropriate application and transitions of technologies listed above
Layers of the Above Soil Types	See the discussion below for appropriate use of technologies listed above

2.3.1. Technologies Appropriate for Soft clay

2.3.1a Excavation and Replacement

Excavation and replacement is the most common and simplest ground improvement technology. Unsuitable soil, such soft clay or highly organic soil, under or near a proposed structure and/or for a given length of roadway is removed and replaced by a good quality material, to the extent required to maintain stability or to avoid detrimental settlement of the structure. Sand and gravel are often preferred as replacement materials because they are easy to compact, strong, relatively insensitive to moisture changes, and they have low compressibility. However, other types of on-site soils or borrow material are often more economical choices and may be used when conditions permit. The backfill is generally placed in lifts, and each lift is compacted, which increases the density and strength of the soil, enabling it to withstand a higher load with less deformation. When moisture sensitive soils are used as backfill, the water content of the backfill should be near optimum for compaction. Excavation and replacement also permits the inclusion of geosynthetic materials to improve the engineering behavior of the replacement material.

Cost effective use of excavation and replacement is limited by the depth of soft soil. High groundwater table and/or very soft soils can prevent the use of conventional earth moving equipment, and also limit the cost effectiveness of this technique.

2.3.1b Prefabricated Vertical Drains with Fill Preloading

Prefabricated Vertical Drains (PVDs) are band shaped (rectangular cross-section) products consisting of a geotextile filter material surrounding a plastic core. PVDs are used when foundation soils consist of cohesive soils of low strength and permeability and construction on the soils would result in excessive settlement and/or stability problems. The concept behind the use of PVDs is to reduce the length of drainage paths in soil deposits and thereby reduce the time for consolidation of the deposit.

Fill preloading consists of placing a temporary amount of fill soil on top of the foundation soils to induce settlement in the foundation soils. The fill provides an increase in the total stress in the foundation soils, leading to an increase in pore pressures that then dissipate with time, resulting in consolidation of the foundation soils. Consolidation results in an increase in unit weight of the soils with consequent increase in strength and decrease in future settlement potential. The fill preloading can be done in stages to avoid instability around the perimeter of the filled area. Preloading with embankment fill is one of the oldest techniques to improve soft cohesive soils.

2.3.1c Vacuum Preloading with and without PVDs

Vacuum preloading is a technique that induces an increase in effective stress in the foundation soils through a reduction in pore pressures and is an effective means for improvement of saturated soft soils by consolidation. The soil site is covered with an airtight membrane and a vacuum is created underneath it by using a dual venturi and vacuum pump. The technique can be used with or without vertical drains into the foundation soils; however, the addition of vertical drains increases the effectiveness of the method by accelerating the rate of consolidation. The technology can provide an equivalent pre-loading of up to about 15 ft (4.5 m) high conventional soil fill surcharge.

2.3.1d Various Types of Columns

There are several types of columns that can be used to treat or bypass the unstable foundation soils. Treating the soil involves improving a soil parameter to achieve a desired result such as densifying the soil or to increase the strength or reduce the permeability. Bypassing the poor soils is performed to reach and utilize more stable characteristics of deeper soils. Traditional pile foundations are a common way to bypass unstable soils. The column types used to treat or bypass the soil include sand compaction columns, aggregate columns, vibro-concrete columns, continuous flight auger piles, geotextile encased columns, micropiles and the CSV soil stabilization system. For a full description of each column type and applicability see the fact sheets attached to this report or information in the Information & Guidance System.

2.3.1e Construction Platforms

Geosynthetics (i.e., geogrids, woven geotextiles, and geocells) are used as basal reinforcements beneath a granular fill to form a temporary construction platform to support construction equipment and traffic over soft soil in order to avoid the formation of mud waves and excessive ruts. When geosynthetics are used at the interface between subgrade (soft soil) and subbase (granular fill) to support construction traffic, it is commonly referred as geosynthetic-reinforced unpaved roads or haul roads. Construction platforms may be used over soft soils to support PVD installation equipment, column construction equipment, for access to place geosynthetic embankment reinforcement material and embankment fill, or to support deep mixing equipment.

2.3.1f Deep Mixing Methods

Deep mixing refers to the blending of cement, lime, slag, and/or other binders in powder or slurry form to stabilize soil in-situ. When the binder is in powder form, the method is commonly referred to as the dry method. When the binder is in slurry form, the method is commonly referred to as the wet method. The choice of application method will depend upon the characteristics of a particular site and the desired performance characteristics of the treated soil. Mixing can be done with single-axis rotating tools to create single columns, multiple-axis rotating tools to create a set of overlapping columns in a single stroke, chainsaw-like mixing equipment to create continuous panels, mixing probes for mass stabilization, or other devices. For dry- and wet-method rotary mixing tools, binders are injected through the hollow stem of the rotating tool.

2.3.2. Technologies Appropriate for Loose sand

2.3.2a Vibrocompaction

Vibrocompaction is a method of deep densification of cohesionless soil through penetration using a vibrating probe to rearrange soil particles around the probe into a denser state. This technology has been used in the U.S. since 1948. It has been commonly and successfully used for clean sands with a silt content less than 15% and/or clay content less than 2%. Vibrocompaction is usually restricted to depths less than 100 ft (30 m), with successful treatment to considerably greater depth (maximum of 200 ft (60 m)) in some cases.

2.3.2b Deep Dynamic Compaction

Deep Dynamic Compaction (DDC) is a method of ground improvement for densifying marginal materials in-place through the application of high levels of energy at the ground surface. The energy is applied by repeatedly raising and dropping a tamper with a mass ranging from 5 to 40 tons (45 to 350 kN) from heights ranging from 30 to 120 ft (9 to 37 m). In most cases the tamper is lifted and dropped using a specially adapted conventional crane. The tamper's energy of impact at the ground surface results in densification of the deposit to depths that increase with the magnitude of the energy applied. The depth of significant improvement generally ranges from about 10 to 30 ft (3 to 9 m) for light- to heavy-energy applications, respectively. Following the high energy level application, the surface of the deposit is in a loose condition to a depth about equal to the depth of the craters. The ground surface is then compacted by repeatedly dropping a light-weight ironing (i.e., low energy level) tamper in a tight grid pattern.

2.3.2c Rapid Impact Compaction

Rapid Impact Compaction (RIC) is a process that provides controlled impact compaction of the earth using excavator mounted equipment with a 5 to 9 ton (45 to 80 kN) weight (7.5 ton (67 kN) common) which is dropped approximately 4 ft (1.2 m) onto a 5 ft (1.5 m) diameter tamper capable of imparting 40 to 60 blows per minute. The resulting force can densify soils to depths on the order of 10 to 20 ft (3 to 6 m). The depth of compaction is dependent on the soil properties, groundwater conditions, and compaction energy. Evidence suggests that the higher the energy input, the greater the depth of compaction for some soils. The initial blows in RIC create a dense plug of soil immediately beneath the tamper. Further blows advance the compaction zone.

2.3.2d High Energy Impact Rollers

High Energy Impact Rollers are essentially non-circular (three-sided, four-sided, to five-sided) shaped tow-behind solid steel molds that typically vary in weight from about 8 to 12 tons (71 to 107 kN). The impact compaction energy is transferred to the soil by means of the lifting and falling motion of the non-circular rotating mass. The type of compactor to use depends on the soil type and moisture regime and depth of treatment needed. The rollers are pulled at relatively high speeds (typically from about 10 to 12 mph (6 to 7 km/h)) to generate a high impact force that reportedly can densify material to depths greater than 3 ft (1 m).

2.3.2e Blast Densification

In blast densification, often referred to as explosive compaction, densification occurs after an explosive charge is detonated below the ground surface. Blast densification is generally a technique for densifying loose, relatively clean, cohesionless soils. The detonation of explosives induces liquefaction in the soils, which then consolidates to a denser, more stable configuration under the pressures induced by the blast and by gravity. In blast densification, charges are placed in pre-drilled or jetted holes that are located in a lateral grid pattern with charge spacings typically between 10 and 50 ft (3 and 15 m). Several charges are fired at once, with delays between charges to enhance cyclic loading while minimizing peak acceleration. Often multiple passes of charges are required to reach the desired densification. The vertical spacing of the charges varies with the size of the charges and thickness of the layer to be densified. Blast densification has been used to improve soils to depths of up to 130 ft (40 m). The maximum depth to which this technique may be effective is not known. Volume improvements of 4 to 10% have been reported, with relative density increases in the range of 10 to 40%. This technique has been used for densifying saturated alluvial deposits, hydraulic fills, and volcanic debris flows. If a partly saturated soil is prewetted before the charges are detonated, the process is termed hydroblasting, a method that has been used to treat collapsible soils.

2.3.3. Technologies Appropriate for Soft/loose silt

The foundation improvement technologies used to improve clay soils (see above) can also be used to improve soft/loose silts. In addition, depending on the percentage of the silt particles, several of the techniques to improve loose sands may be applicable to silty soils. For example, although they are less effective for densification of fine-grained soils, stone columns at closer spacings with larger area replacement ratios can be used to densify silty soils. The Information & Guidance System should be consulted for additional information about the use of a specific technology in silty soils.

2.3.4. Layers of the above soil types

When the site soil contains layers of different soil types such as sand and clay, some of these technologies may not be as useful. For example, if a loose sand layer is overlain by clay or by a denser sand layer, deep dynamic compaction will be much less effective or not useful. Blast densification should not be used if there are clay layers within a sand deposit. Also, certain types of columns such as deep mixing method columns are less effective in layered soils.

2.4. Embankment Technologies

The embankment above the unstable soils is traditionally constructed with conventional fill placement and compaction procedures. The following section summarizes additional technologies that may be used in embankment construction. Further information can be found in the Information & Guidance System.

2.4.1. Reinforced soil slopes

Reinforced soil consists of tensile reinforcements added to soil to form a composite material which is stronger than the individual components. Reinforced Soil Slopes (RSSs) are a form of mechanically stabilized earth that incorporates planar reinforcing elements in constructed earth-sloped structures with face inclinations less than 70º from the horizontal. Multiple layers of geogrids, geotextiles, steel welded wire mats, or woven steel mats may be placed in an earthfill embankment slope during construction to reinforce the soil and provide a stable, sloped faced earth structure. Facing treatments ranging from vegetation to flexible armor systems can be included to prevent raveling and sloughing of the face. The primary purpose for using reinforcement is to construct an RSS embankment at an angle steeper than could otherwise be safely constructed with the same embankment fill soil.

2.4.2. Geosynthetic reinforced embankments

In geosynthetic reinforced embankments, a geosynthetic is typically placed on the ground surface or near the bottom of the embankment prior to placement of the embankment fill material. The geosynthetic can be either a geotextile, geogrid, or a combination of the two. A granular material is typically placed above the geosynthetic to aid in compaction and in drainage. The reinforcement is used to increase stability and resistance to deep, rotational embankment foundation failures. The reinforcement will not reduce the magnitude of vertical settlement of the embankment, but will reduce differential vertical settlements.

2.4.3. Column supported embankments

When an embankment is to be constructed over ground that is too soft or compressible to adequately support the embankment, columns of strong material can be placed in the soft ground to provide the necessary support by transferring the embankment load to an underlying firm stratum. There are numerous types of columns that may be used for this technology. A list of commonly used columns is given in Table 2. A load transfer platform or bridging layer may be constructed immediately above the columns to help transfer the load from the embankment to the columns, and thereby permit larger spacing between columns than would be possible otherwise. Load transfer platforms generally consist of compacted soil and multiple layers of geosynthetic reinforced select granular fill.

Table 2. Columns commonly used for column supported embankments

aggregate columns
vibro-concrete columns
deep mixing methods columns
continuous flight auger piles
driven piles with or without pile caps

2.4.4. Lightweight fill

The compacted unit weight of most fill soils consisting of gravels, sands, silts, and/or clays ranges from about 115 to 135 lb/ft^3 (18 to 21 kN/m^3). On some projects, it is desirable to use a material with a lower unit weight in order to reduce the magnitude of applied loads. The use of conventional earth fill material in embankment applications could result in excessive settlement or a lower than desired factor of safety against deep-seated stability failure. The use of a lightweight embankment fill material decreases the vertical load and the destabilizing force, and results in reduced settlement and increased stability.

Many types of lightweight fill materials have been used for roadway embankment construction. Some of the more common lightweight fills are listed in Table 3 below. There is a wide range in unit weight of the lightweight fill materials, but all have unit weights less than conventional soils.

Table 3. Common Lightweight Fills

Material	**Unit Weight Range (lb/ft^3)**
Conventional earth fill	115 to 135 (18 to 21 kN/m^3)
Geofoam (EPS)	1 to 2 (0.2 to 0.3 kN/m^3)
Foamed concrete	23 to 60 (3.6 to 9.4 kN/m^3)
Wood fiber	45 to 60 (7.1 to 9.4 kN/m^3)
Shredded tires	45 to 55 (7.1 to 8.6 kN/m^3)
Expanded Shale, Clay & Slate (ESCS)	40 to 55 (6.3 to 8.6 kN/m^3)
Fly Ash	70 to 90 (11 to 14 kN/m^3)
Boiler Slag	90 to 110 (14 to 17 kN/m^3)
Air-Cooled Slag	70 to 95 (11 to 15 kN/m^3)

2.4.5. Mechanically stabilized earth walls

The use of reinforced soil retaining wall structures has developed over the past few decades into a conventional grade separation solution. Reinforced soil consists of tensile reinforcements added to soil to form a stronger composite material mass. Reinforced soil structures are generally classified as a wall when the face batter is equal to or greater than 70 degrees from horizontal, and are classified as Reinforced Soil Slopes (RSS) when the face batter is shallower. Mechanically stabilized earth (MSE) walls are more flexible than conventional retaining walls and, therefore, are suitable for sites with poor foundation soils and in seismically active areas.

MSE walls can be used on the sides of embankments to decrease the width and fill volume of the embankment, provided that the foundation has been improved to provide adequate bearing capacity.

2.5. Integration

There are many possible different combinations of the technologies used above; however, there are a number of combinations that are more likely to be successful. These combinations are used for many reasons. For example blast densification does not densify the soil in the upper 5 ft (1.5 m) of soil below the ground surface. This soil can be compacted by a shallow compaction method such as rapid impact compaction. Prefabricated vertical drains and fill preloading can be used with many types of columns or densification methods such as blast densification or deep dynamic compaction to improve the densification results.

Light weight fills can be used to reduce the load on columns. Numerous successful combinations that were found during a literature review are noted in Table 4. Case histories that detail a number of these combinations are summarized in the subsequent section.

Table 4. Technology combinations found in literature review

	PVDs and Fill Preloading	Vacuum Preloading w/ and w/o PVDs	Vibrocompaction	Deep Dynamic Compaction	Blast Densification	Aggregate Columns	Geotextile Encased Columns	Deep Mixing Methods	Jet Grouting	Soil Nailing	Mechanically Stabilized Earth Walls	Reinforced Soil Slopes	Light Weight Fills	Column Supported Embankments	Micropiles
PVDs and Fill Preloading			X			X		X			X		X		
Vacuum Preloading w/ and w/o PVDs							X								
Vibrocompaction	X				X	X									
Deep Dynamic Compaction					X	X					X				
Blast Densification			X	X											
Aggregate Columns	X		X	X							X				
Geotextile Encased Columns		X										X			
Deep Mixing Methods	X										X		X		
Jet Grouting										X					X
Soil Nailing									X						X
Mechanically Stabilized Earth Walls	X			X		X		X							
Reinforced Soil Slopes							X								
Light Weight Fills	X							X						X	
Column Supported Embankments													X		
Micropiles									X	X					

Note: A blank cell means no case histories were located for that combination.

CHAPTER 3

CASE HISTORIES

3.1. Case History Summaries

This section provides summaries of several case histories of projects where ground improvement technologies have been combined. These were chosen to highlight several different combinations and to give the different reasons/benefits of combining these technologies. Each summary contains the following information to the extent reported:

- the technologies that were combined
- the reference from which the case history was obtained
- details on the geometries of installation of each technology
- how the technologies were combined
- why they were combined
- the advantages gained

3.1.1. Deep Mixing Methods and Prefabricated Vertical Drains

Several case histories where deep mixing methods (DMM) were combined with prefabricated vertical drains (PVD) were found. Two of these, Liu et al. (2008) and Ye et al. (2006) include research into the best configuration of DMM columns and PVDs. In the case history presented in Liu et al. (2008), DMM columns and PVDs were installed to depths of 40 ft (12 m) in layered clays that extended to depths of 70 ft (21 m). Liu et al. (2008) found that the installation of PVDs between DMM columns reduced the amount of time needed to dissipate pore pressures and increased the rate of increase in bearing capacity in the strengthened soil.

Ye et al. (2006) describe the use of DMM columns with PVDs to improve thick (>82 ft (25 m)) layers of soft soils under embankments. These layers can be improved solely with PVDs and fill preloading, but usually require a long construction time to achieve the necessary settlement. DMM columns become difficult to install correctly at great depths. To correct these problems, previous studies recommended using shorter DMM columns in the upper portion of the soft soils with PVDs installed throughout the depth of the soft soil layer. Ye et al. (2006) used a test embankment on the Huai-Yan Expressway in the Jiangsu Province in China to determine if this combination is effective. The soft silty clay layers extended to depths of up to 55 ft (17 m). They installed DMM columns to depths of 26 ft (8 m) along with PVDs that extended the full depth of the soft layer. Two different configurations were used for the test with column spacings of 4.5 ft (1.4 m) and 5 ft (1.5 m). Because the DMM columns are not supported on a firm stratum, they can move downward easily under a load and do not provide any arching between columns. However, they do help to densify the soil and provide an additional amount of stabilization for the construction of the embankment. Figure 3 (Ye et al. 2006) shows a model of the arrangement of DMM columns and PVDs under an embankment.

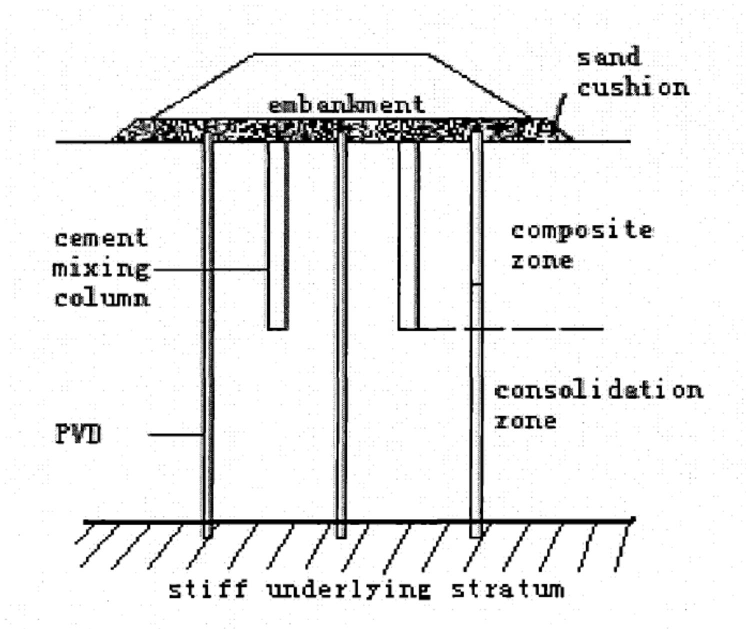

Figure 3. Model showing a combination of DMM columns and PVDs under and embankment from Ye et al. (2006).

3.1.2. Lightweight Fills, Deep Mixing Methods and PVDs with Fill Preloading

On the Woodrow Wilson Bridge replacement project, numerous methods of ground improvement were compared to determine the most cost effective solution that fit the construction schedule and met the criteria for allowable settlement. To complete the project, staged construction with PVDs and fill preloading were used wherever schedule and settlement tolerances would allow, lightweight fills were used in areas above the 100 year flood elevation, and deep mixing methods were used where fill heights did not exceed about 15 to 20 ft (4.5 to 6 m). Where embankment heights extended above these heights, more cost effective bridge solutions were chosen. The details of the deep mixing methods solution can be found in Shiells et al. (2004). The soil conditions consisted of 50 to 82 ft (15 to 25 m) of very soft and highly compressible organic silts and clays. The deep mixing method column geometry for a test embankment is shown in Figure 4 below. 2.5 ft (0.8 m) diameter columns were installed through the entire depth of the poor soil layer and were spaced at 6.0 ft to 10.0 ft (1.8 to 3 m) center-to-center. The final configuration is not stated and this omission may be due to the use of a performance approach specification to allow the contractor to determine the best mix design and geometry for the columns.

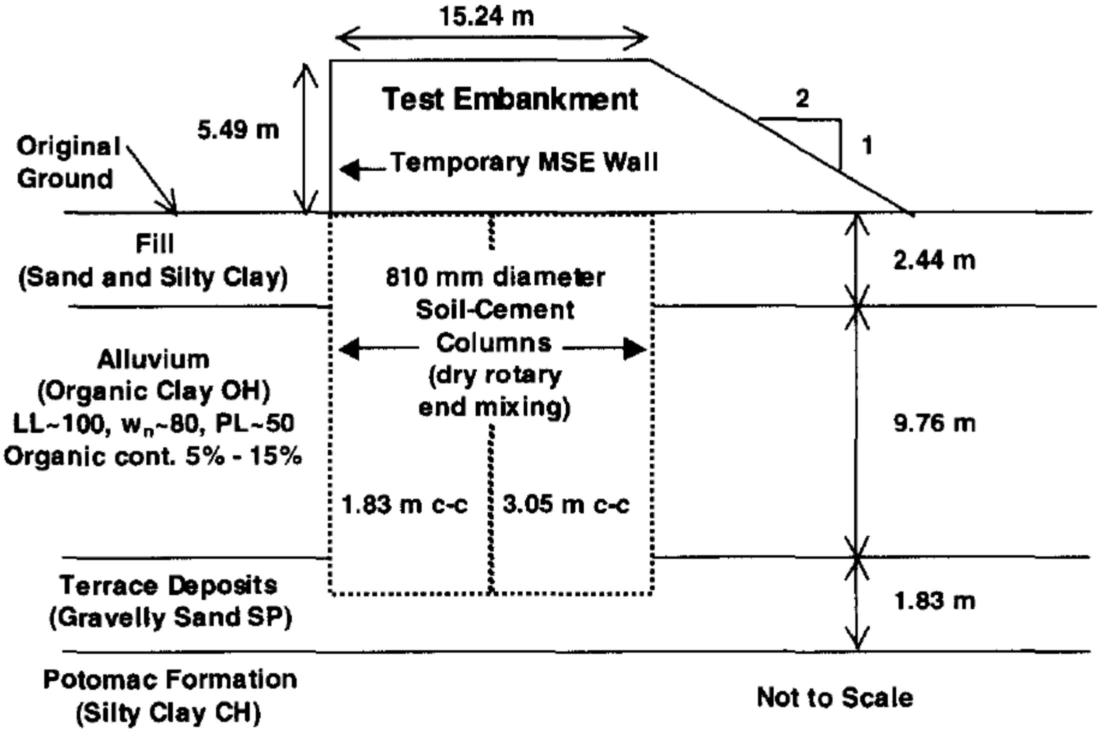

Figure 4. Test embankment configuration for deep mixing method columns from Shiells et al. (2004) (1 m = 3.28 m).

3.1.3. Aggregate Columns and PVDs

Rollins et al. (2006) describe ground improvement details for liquefaction mitigation for a highway overpass project in Farmington, Utah. The soils at the site consisted of a 10.8 to 14.1 ft (3.3 to 4.3 m) thick liquefiable layer of interbedded layers of silty sand and sandy silt beneath a 9.8 ft (3 m) thick layer of silty gravel and clay. The median fines content of the liquefiable layer was approximately 53%. This high fines content reduced the potential effectiveness of aggregate columns while increasing the installation cost and difficulty. Due to aggregate column installation problems experienced at a nearby site, a test plan was developed to determine whether the installation of prefabricated vertical drains would increase the effectiveness of the aggregate columns in a soil with a high fines content. Based on the increased effectiveness of the aggregate columns combined with PVDs in soils with a high fines content seen in the test program, the full production plan required 3.6 ft (1.1 m) diameter aggregate columns in a 6.6 ft center-to-center spacing in a triangular pattern with wick drains placed at the midpoint between each column. This wick drain placement resulted in six wick drains around each column placed

3.3 ft (1 m) away from each column. The area replacement ratio – defined as the area of the aggregate column divided by the area of the unit cell around the column – for the chosen spacing is 27%. Figure 5 shows a plan view of the aggregate column and PVD arrangement. The PVDs were installed prior to installing the aggregate columns, but no mention is made of the depth of installation of these PVDs. The aggregate columns were installed to a depth of around 21.3 ft (6.5 m) using the dry bottom feed vibro-compaction method. During installation, water came out of PVDs at distances of up to 19.7 ft (6 m) away from the location of the column being installed showing that PVDs, even at a distance, can help dissipate porewater pressures. Based on comparisons with other aggregate column projects, the authors determined that the combination of PVDs and aggregate columns in the sand with a higher fines content at a replacement ratio of 27% was as effective as aggregate columns in cleaner sands (<15% fines) with an area replacement ratio of between 10 and 15%.

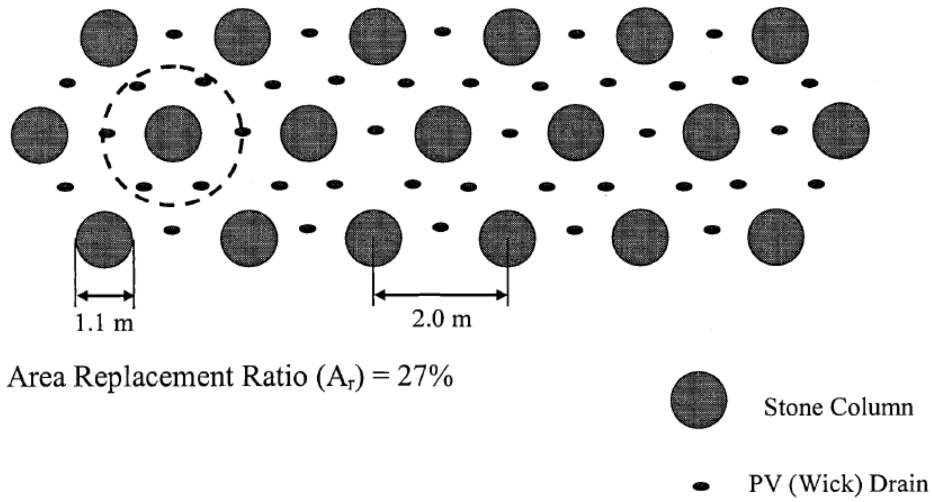

Figure 5. Arrangement of aggregate columns and PVDs from Rollins et al. (2006).

3.1.4. Aggregate Columns and Deep Dynamic Compaction

Mitchell and Welsh (1989) describe the use of aggregate columns and deep dynamic compaction at the Steel Creek Dam site in South Carolina to reduce the liquefaction potential of the soils. Deep dynamic compaction was used to densify soils up to 29.5 ft (9 m) deep in the valley section of the dam. Where soils were too deep for deep dynamic compaction to be effective, aggregate columns were installed to depths of up to 69.9 ft (21.3 m) using the dry bottom feed vibro-compaction method. The authors found that both technologies were effective in soils with less than 10% clayey fines.

Based on the case history presented in Bayuk and Walker (2009), another way to combine aggregate columns and deep dynamic compaction is to place the columns at the center of each compaction point. This was done at the site of a one story retail store. The ground conditions consisted of 10 to 15 ft (3 to 4.6 m) of loose to very dense fill and building rubble underlain by 3 to 6 ft (1 to 2 m) of peat and organic silt above a thick deposit of varved clays and silts. A test section using only deep dynamic compaction was performed, and the contractor found that while the upper layer of fill was densified as required, the energy from the compaction could not push the fill into organic soils to provide the necessary strength. Because of this problem, the contractor chose to install aggregate columns along with dynamic compaction in areas of the site where additional strength was needed. The deep dynamic compaction points were spaced at 12 ft (3.7 m), and the tamper was dropped 8 times at each print. Aggregate columns 3.5 ft (1.1 m) in diameter were installed to an average depth of 14 ft (4.3 m) at each tamper drop point. The test section that included aggregate columns showed a settlement approximately 20% less than the test with deep dynamic compaction alone, and it reduced the differential settlement between the areas of the foundation improved with the combined technologies. In addition, the use of aggregate columns strengthened the soil enough to allow shallow foundations to be used everywhere except under a parking garage on the site.

3.1.5. Column Supported Embankments and Lightweight Fill

Lightweight fills were used alongside a column supported embankment to support the expansion of Trunk Highway (TH) 241 near St. Michael, Minnesota. According to Wachman and Labuz (2008), this section of the highway was bordered by a pond on one side and a marshy section on the other. The ground conditions under the west side of the highway consisted of 30 ft (9 m) of highly organic silt loams and peats above approximately 20 ft (6 m) of silty organic soils. Beneath this layer the ground consisted of 12 ft (3.7 m) of loamy sand and 35 ft (10.7 m) of gravelly sand. The bedrock beneath this consisted of well-cemented sandstone. Due to the depth of the soft soils, the Minnesota DOT (MnDOT) chose to build a column supported embankment on the west side of the highway. Because the poor soil on the east side of the highway did not extend to such great depths, MnDOT choose to partially excavate and then surcharge the soil. Following the removal of the surcharge, geofoam fill was used in place of granular fill to reduce the load on the remaining soft soils. The geofoam fill extends across the roadway to the edge of the load transfer platform used in the column supported embankment. The column supported embankment extended approximately 350 ft (107 m) along the highway and was located in close proximity to a railroad line. See Figure 6 below. The use of both column supported embankments and lightweight fill was an efficient way to reduce expected settlement of the soft organic soils and reduce disturbance to surrounding infrastructure during construction.

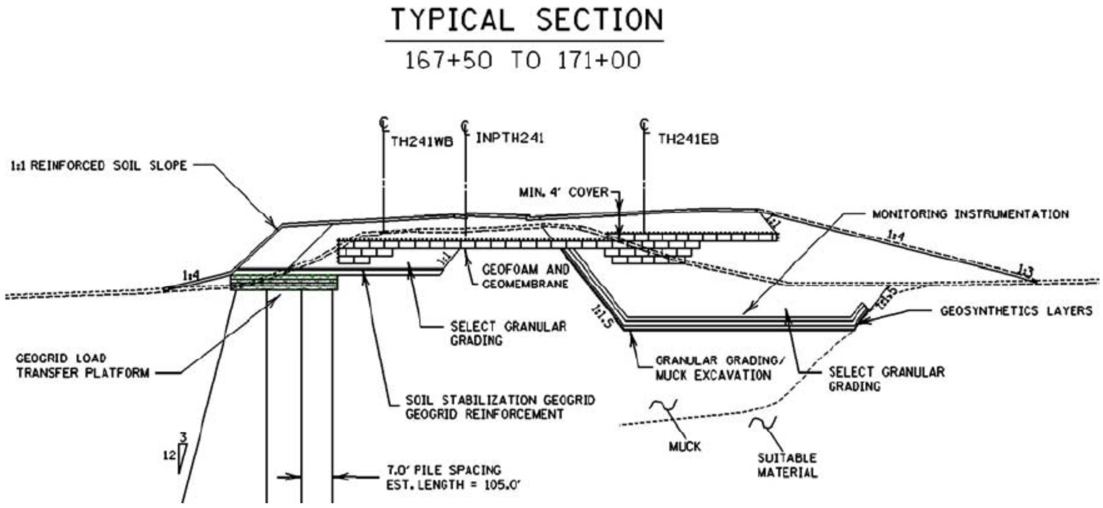

Figure 6. Cross section showing ground improvement beneath TH 241 from Wachman and Labuz (2008)

3.1.6. Vibrocompaction and Deep Dynamic Compaction

According to Hayward Baker (1999), Hayward Baker provided specialized geotechnical construction on the Coal Harbor Marina site in Vancouver, British Columbia. A section of the site required densification at depths of up to 32.8 ft (10 m) to reduce liquefaction potential. This densification was done by deep dynamic compaction in all areas except where the vibrations due to deep dynamic compaction would be detrimental to nearby structures. These areas were densified using vibrocompaction since vibrocompaction can be usually be used within 9.8 ft (3 m) of a building.

3.1.7. Vibrocompaction and Blast Densification

Vibrocompaction and blast densification were combined on the Jebba Dam Project to improve clean sand deposits that extended over 230 ft (70 m) below the ground surface. Mitchell and Welsh (1989) discuss the use of blast densification to improve the deep sand deposits where vibrocompaction was not viable. Vibrocompaction was then used to improve sands to depths of between 33 and 115 ft (10 and 35 m). See Figure 7. To reduce the liquefaction potential of the loose sand, minimum equivalent relative densities of 70 percent in the upper 65 ft (20 m), 60 percent in the next 33 ft (10 m) and 50 percent below that. To achieve these requirements, the vibrocompaction points were spaced approximately 9 ft (2.7 m) apart and the explosive charges were placed 33 ft (10 m) apart in a square pattern. These two ground improvement technologies were combined because vibrocompaction was not feasible at the required depths.

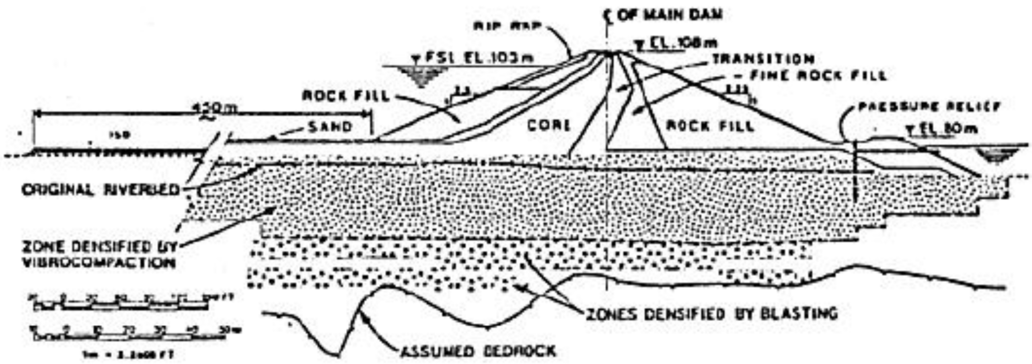

Figure 7. Jebba Dam cross section showing areas improved by vibrocompaction and blast densification from Mitchell and Welsh (1989).

3.1.8. Deep Dynamic Compaction and MSE walls

According to Hayward Baker (1999), in order to improve the ground at the site of a new Dallas Area Rapid Transit (DART) facility, Hayward Baker used deep dynamic compaction to densify the loose soil at the site. After the completion of the DDC, an MSE wall was construction on a portion of the improved site. The loose soil at the site consists of an abandoned sand pit that contains clayey soil and construction debris that extends to a depth of up to 35 ft (10.7 m). Limestone bedrock extends beneath this pit. Two 200 ton (1.8 MN) cranes with 18 ton (160 kN) weights were used. The weights were dropped from heights of up to 80 ft (24.4 m) at 10 to 20 ft (3 to 6 m) spacings. The spacing was varied throughout the site to ensure the site was densified uniformly. A 950 ft (290 m) long MSE wall of varying heights (no quantitative height information given) was installed at the north edge of the site after completion of deep dynamic compaction in that area

3.1.9. Vibrocompaction and Aggregate Columns

According to Daramalinggam et al. (2009), for the construction of storage tanks near Seraya Place in Jurong Island, Singapore, numerous combinations of aggregate columns and vibrocompaction were used for construction. Soil conditions varied greatly but included a layer of sand fill that ranged from 6.6 to 75.5 ft (2 to 23 m) in depth underlain by a layer of clay. Where the vibrocompaction was used over aggregate columns, the sand layer ranged from 16 to 32 ft (5 to 10 m) thick and the clay layer ranged from 3 to 23 ft (1 to 7 m) thick. Beneath eight tanks, aggregate columns were placed in a clay layer and vibrocompaction was used to densify the sand layer above the clay layer. Figure 8 shows the different ground improvement technologies that were used to improve the soil under the tanks.

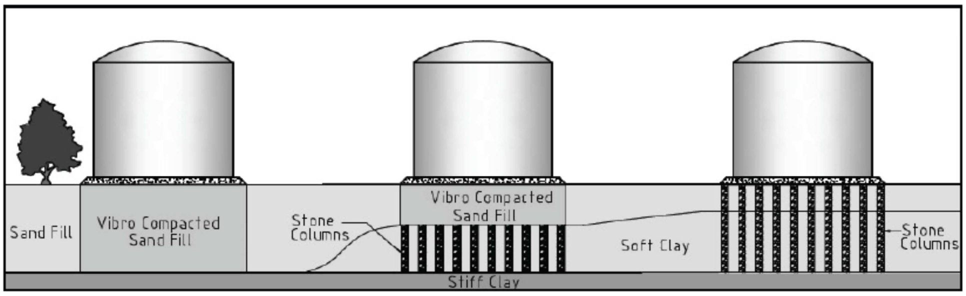

Figure 8. Different foundations used under tanks based on subsurface conditions from Daramalinggam et al. (2009).

3.1.10. Aggregate Columns and MSE Walls

Munoz and Mattox (1977) present one of the early combinations of MSE walls above aggregate columns and one of the first uses of aggregate columns on a highway project in the United States. During the reconstruction of the Clark Fork Highway in northern Idaho, the original designs for embankments built at the edge of Lake Pend Orielle were found to be inadequate due to a lack of information on the soil conditions. Subsequent borings were made and determined that there was a layer of loose sandy silt. Due to the site constraints of upgrading a highway between the lake and a Northern Pacific Railroad rail track, the designers determined the best way to build the embankment was to improve the loose sandy silt with aggregate columns and construct an MSE wall over the aggregate columns for a 500 ft (152 m) section of the alignment. The aggregate columns were installed in a triangular array at spacings of 7 ft (2 m). No information is given on the height of the MSE wall or the depth of installation of the aggregate columns. The use of aggregate columns reduced the risk and cost that would have been associated with installing a piled foundation on the shoreline where the bedrock dips at a very steep angle. The combination of aggregate columns and an MSE wall reduced the cost for the project and the wall was completed a month and a half ahead of schedule.

A more recent application of aggregate columns beneath an MSE wall is detailed in Raju (2009). The Pantai Dam Interchange on the New Pantai Expressway in Malaysia was built over very soft to soft silts that ranged from 16.4 to 39.4 ft (5 to 12 m) deep. The interchange contained both embankments and MSE walls. Aggregate columns were chosen to reinforce the soil under the foundations of these structures because they were quick to construct and they cost less than a traditional pile foundation. Figure 9 shows the placement of the aggregate columns beneath the MSE walls.

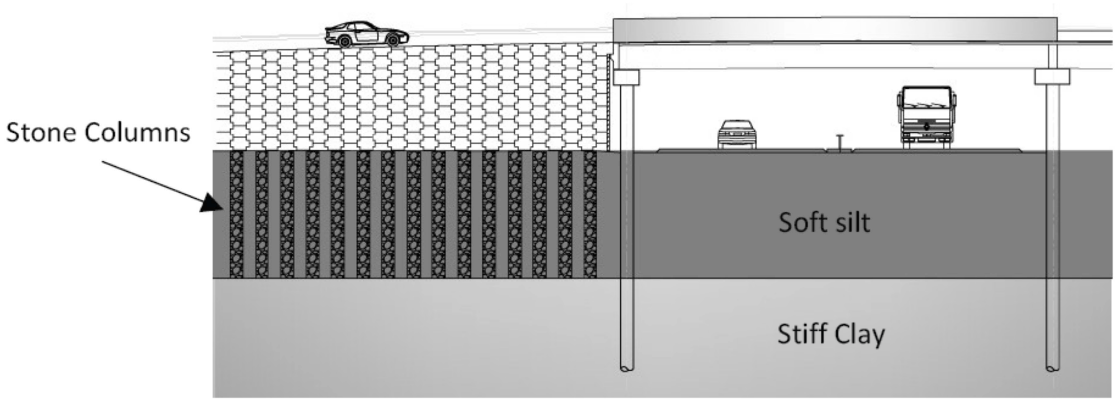

Figure 9. Aggregate columns placed beneath MSE walls on the Pantai Dam Interchange from Raju (2009).

3.1.11. Deep Mixing Methods and MSE walls

Dasenbrock (2005) outlines the use of deep mixing method (DMM) columns beneath an MSE wall at the intersection of Glen Road and US 10/US 61 in the Minneapolis/St. Paul area. The original geotechnical investigations found that the soil in the area consisted mostly of fairly uniform sandy soil deposits above dolostone bedrock, and the original foundation design was based on this. However, subsequent investigations found a large pocket of compressible clay that ranged from 10 to 60 ft (3 to 18 m) in depth. It was estimated that the settlements in this clay layer would exceed the allowable deflection in the bridge foundations and embankments. In addition this clay layer occurred beneath some of the highest embankment fills which exceeded 30 ft (9 m) in height. A comparison of ground improvement technologies found that DMM columns would meet the performance criteria, require the least amount of redesign and reduce impact to the construction schedule. DMM columns were not the least costly solution, but they were the best option based on all the design considerations. Table 5 from Dasenbrock (2005) shows the different design alternatives considered. Based on monitoring results from later in the project, DMM columns are a viable option for improving soft soils under MSE walls.

Table 5. Table from Dasenbrock (2005) showing comparison of ground improvement technologies for use beneath a MSE wall

Alternative	Lightweight Fill*	Soil Surcharge	DMM	H-Pile Mat Foundation
Design Time	Substantial re-design of structural system	Moderate; check stability; impact on RR	Performance specification required (contractor)	Moderate to large re-design of footings, walls and bridge
Problem or potential problems	Design standards; experience; long term creep; design life	Railroad and utility impacts; substantial fill height required; sheet pile	Inexperience with method; QA oversight	Significant number of pile required; drag-load; pile driving time; noise
Construction time	Probably accelerated unless difficulties occur	Large amounts of earth moving	Depends on production. Expected to be faster than surcharging	Time to drive 4000 piles
Redesign of structural system	Yes, Panels, Footings	No	No	Yes, Footings, Pile Design
Estimated Costs	$4 M	$3 M	$3.6 M	$4.1 M
Technique Benefits	No net load	Cost Effective	No redesign of structures	Verifiable capacity

*Expanded polystyrene (EPS) (a.k.a. geofoam) was considered for this option.

Another way to combine MSE walls and deep mixing methods was presented in Ito et al. (2006). In this study, several MSE walls were constructed with a soil cement backfill to reduce the tensile stresses on the geogrid reinforcements and to reduce the soil and water stresses on the wall facing. The improved soil extended up to 9 ft (2.7 m) behind the wall facing and the geogrid reinforcement extended up to 22 ft (6.7 m) beyond the improved soil block. Using a soil cement mixture behind the wall facing allowed for the use of clayey soils in the backfill and reduced the strains in the geogrid as the water level in the backfill increased. Figure 10 shows a schematic of the combination of the soil cement backfill and the MSE wall.

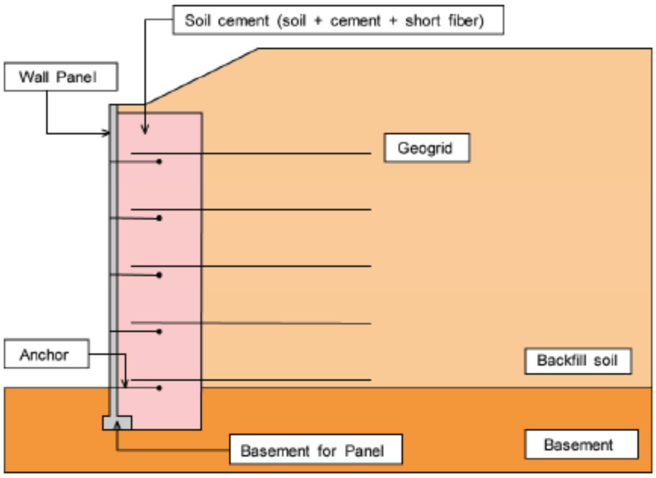

Figure 10. Soil cement mixture behind MSE wall facing panels from Ito et al. (2006)

3.1.12. Multiple Technologies on I15

Based on information from Gunalan and Turner (2000), the reconstruction of Interstate 15 through Salt Lake City utilized multiple ground improvement technologies. These included:

- PVDs with fill preloading to accelerate consolidation
- Deep Mixing Method (DMM) columns to provide stability and reduce settlements
- working platforms with geotextiles to improve stability during embankment construction
- lightweight fill to reduce settlements
- MSE walls to deal with limited right-of-way issues.

The soil in this area generally consisted of 33 to 100 ft (10 to 30 m) of layers soft to medium stiff plastic clay and loose silty sands underlain by medium stiff to stiff clay, underlain by medium dense to dense sand and gravel.

Based on settlement calculations performed during the bidding process, the design/build contractor determined that the embankments would settle up to 12 to 14% of the height of the fill. This would result in settlements of up to 5.9 ft (1.8 m) beneath the tallest embankments. Up to 1 ft (0.3 m) of secondary compression was expected to occur in the 10 years after construction. Several large retaining walls (up to 40 ft (12 m) high) would have to withstand large settlements.

PVDs with fill preloading were used in a 5.7 ft (1.7 m) triangular spacing to varying depths based on the stratigraphy of the specific section. Lime-cement DMM columns were installed in two test areas, and 2.0 ft and 2.6 ft (0.6 and 0.8 m) diameter columns were used. In one of the areas, they were installed under the edge of one of the MSE walls to reduce the predicted

settlement. Although the columns performed well and provided almost immediate strength gain, they were difficult and slow to install so were only used in the two test sections.
High strength geotextiles were used to create working platforms where the PVDs were too slow to provide adequate strength gain before embankment construction began. To reduce the number of geotextile layers used, a thick geotextile with a strength of 24 k/ft (350 kN/m) at 6% strain was used for the majority of layers, and a geotextile with a strength of 10 k/ft (150 kN/m) at 6% strain was used in the rest of the layers. An 8 in. (200 mm) thick layer of sand was placed between geotextile layers. There is no mention of the number of layers used for each working platform.

To reduce settlements of existing utilities, geofoam with a unit weight of approximately 2 pcf (0.3 kN/m^3) was used when embankments were constructed over these utilities. In other areas, lightweight fill was used to reduce embankment settlements and to prevent subsurface soils from exceeding the preconsolidation pressures. Blast-furnace slag with a unit weight of approximately 95 pcf (15 kN/m^3) and a scoria material with a unit weight of approximately 60 pcf (9.5 kN/m^3) were used as the lightweight fill material, with scoria used most often due to a shortage of blast-furnace slag.

All of these ground improvement techniques were used to accelerate construction while providing stability and reducing settlement. Because this project was completed as a design/build project, the contractor combined multiple techniques to provide the most cost effective and efficient construction program.

3.1.13. MSE walls and Prefabricated Vertical Drains

During construction on National Highway (NH) 6 from Dankuni to Kolaghat and Kolaghat to Kharagpur in India, prefabricated vertical drains were used to improve soils beneath mechanically stabilized earth walls. According to Biswas and Adhikari (2006), the soil along the alignment consists of very soft to soft silty clay extending greater than 33 ft (10 m) below ground surface. The designers chose to use PVDs and staged construction for all MSE walls over 16 ft (4.9 m) in height. The heights of the walls where PVDs were used ranged from 20 to 40 ft (6 to 12 m). The PVDs were spaced at 5 ft (1.5 m) center to center in a rectangular pattern and extended 40 ft (12 m) in depth. Figure 11 shows the arrangement of the MSE walls over the PVDs. This combination allowed the majority of the MSE walls to be constructed on the poor soils without any wall failures or large differential settlements.

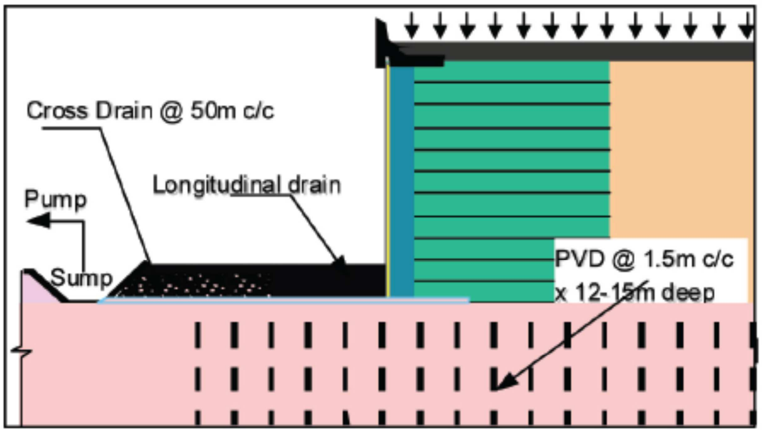

Figure 11. Cross section of MSE wall and PVD arrangement from Biswas and Adhikari (2006)

3.1.14. Reinforced Soil Slopes and Geotextile Encased Columns

Two landscaped embankments were built during the construction of a housing project in the Netherlands. These embankments were built using reinforced soil slopes. Due to the presence of clay under the foundation that was too soft for aggregate columns to be effective, geotextile encased columns (GECs) were used to increase the stability of the embankments. According to Brokemper et al. (2006), the embankment called Bastion West, which was built to a height of 18 ft (5.5 m), was expected to settle 5 to 6 ft (1.5 to 1.8 m) due to the consolidation of a 25 ft (7.6 m) thick organic clay and peat layer in the foundation. To speed up the construction time and reduce the post construction settlement, GECs were installed in the foundation of the embankments. For the Bastion West foundation, 2.6 ft (0.8 m) diameter GECs were installed in a triangular pattern at a spacing of 6.5 ft (2 m) through the entire depth of the soft clay layer. In addition to providing stability, the GECs acted as vertical drains and increased the rate of consolidation. The use of GECs reduced the estimated settlement of the embankment to less than 1.3 ft (0.4 m). Figure 12 shows the layout of the embankment with the reinforced soil slopes and the GECs.

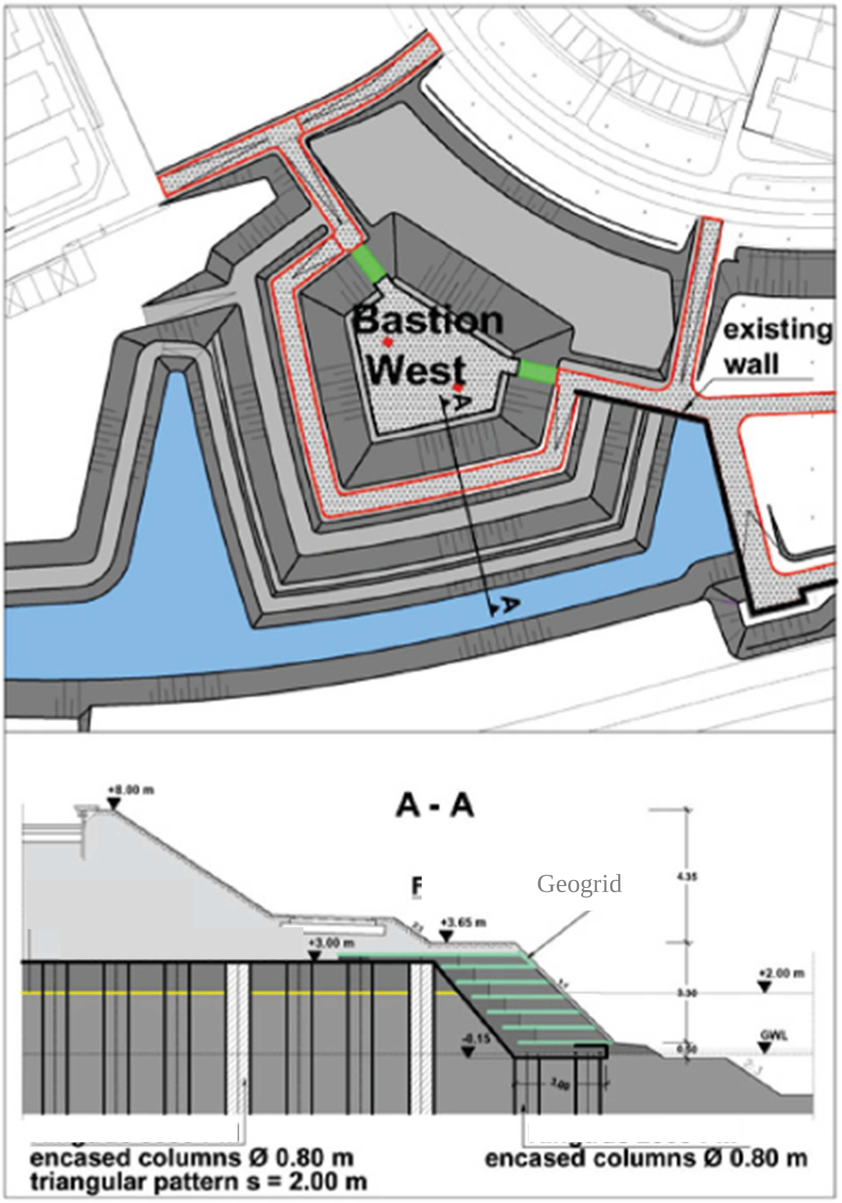

Figure 12. Plan and elevation views of Bastion West showing the location of the GECs beneath the reinforced soil slope after Brokemper et al. (2006)

3.2. Other Case Histories

Additional case histories found in the literature that are not summarized within this paper are listed in Table 6. The majority of these references contain case histories detailing ground improvement combinations that have been summarized above. Others are combinations that are not often used for embankment construction, but provide useful information about combining ground improvement technologies.

Table 6. Technology combinations not summarized in this paper

Technologies Combined	Reference
Deep mixing methods and PVDs with fill preloading	Lin and Wong (1999)
Vibrocompaction and PVDs with fill preloading	Raju (2009)
Aggregate columns and PVDs with fill preloading	Yee and Chua (2009) Rollins et al. (2009) (theoretical study) Alam and Ha (1999)
Aggregate columns and deep dynamic compaction	Varaksin et al. (2009)
Vibrocompaction and deep dynamic compaction	Berthier et al. (2009)
Jet grouting and soil nailing	Hayward Baker (2001a)
Micropiles and soil nailing	Hayward Baker (2001b)
Geotextile encased columns and vacuum preloading	Chu et al. (2009)
Deep mixing methods, sand compaction piles and sand drains	Kitazume (2009)
Jet grouting and micropiles	Pinto et al. (2009)
Deep dynamic compaction and blast densification	Murray et al. (2005)
MSE walls and aggregate columns	Masse et al. (2007)

3.3. Other possible combinations

While the combinations listed in Table 4 and Table 6 were found in the literature review, there are many other combinations of ground improvement technologies that can be used. Table 7 provides other combinations that: (i) the SHRP 2 R02 researchers have seen in practice, (but a case history was not readily located); or (ii) that the SHRP 2 R02 team members believe would be successful combinations based on the current understanding of each technology.

Table 7. Additional combinations of ground improvement technologies

Excavation and replacement	PVDs and fill preloading deep dynamic compaction rapid impact compaction geosynthetic reinforced embankments light weight fills column supported embankments reinforced soil slopes
PV drains and fill preloading	sand compaction piles deep dynamic compaction vibro-concrete columns geosynthetic reinforced embankments
Geosynthetic reinforced embankments	vibrocompaction deep dynamic compaction rapid impact compaction deep mixing methods MSE walls reinforced soil slopes column supported embankments
Vibrocompaction	deep dynamic compaction vibro-concrete columns reinforced soil slopes MSE walls traditional compaction
Deep dynamic compaction	blasting densification traditional compaction lightweight fills reinforced soil slopes
Light weight fills	rapid impact compaction aggregate columns vibro-concrete columns continuous flight auger piles shored MSE walls MSE walls reinforced soil slopes geosynthetic reinforced embankments

Column supported embankments	deep mixing methods MSE walls reinforced soil slopes
Reinforced soil slopes	sand compaction piles rapid impact compaction aggregate columns vibro-concrete columns continuous flight auger piles deep mixing methods
Mechanically stabilized earth walls	sand compaction piles rapid impact compaction vibro-concrete columns CSV soil stabilization system continuous flight auger piles micropiles

CHAPTER 4

CONCLUSION

4.1 Conclusion

This paper provides examples of a number of combinations of ground improvement technologies. It details how and why different ground improvement technologies were combined including the geometry of the combination and the advantages of the combination. It does not provide design or quality control/quality assurance procedures for the ground improvement program nor does it give all possible combinations of ground improvement technologies. The engineer should use this paper in conjunction with the information contained in the Information & Guidance System to create a site specific design that provides the most effective ground improvement program.

CHAPTER 5

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APPENDIX

The following Fact Sheets can be found attached to this report. Additional information can be found in the Information & Guidance System.

Excavation and Replacement
Prefabricated Vertical Drains with Fill Preloading
Vacuum Preloading with and without PVDs
Sand Compaction Piles
Aggregate Columns
Vibro-Concrete Columns
Continuous Flight Auger Piles
Geotextile Encased Columns
Micropiles
CSV Soil Stabilization System
Construction Platforms
Deep Mixing Methods
Vibrocompaction
Deep Dynamic Compaction
Rapid Impact Compaction
High Energy Impact Rollers
Blast Densification
Reinforced Soil Slopes
Geosynthetic Reinforced Embankments
Column Supported Embankments
Lightweight Fill
Mechanically Stabilized Earth Walls

EXCAVATION AND REPLACEMENT

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Excavation of Unsuitable Soil using Hydraulic Excavator in Columbus, Mississippi
(Photograph courtesy of David M. Coleman)

Basic Function

Excavation and Replacement removes unsuitable soils and replaces them with good quality materials to increase the reliability and strength of soil beneath an embankment or pavement structure.

Advantages:

- Simplicity of the technology
- Reliability
- Equipment is readily available
- Contractors are readily available
- Specifying/Contracting is simple

General Description:

Unsuitable soils beneath an embankment or pavement structure are replaced by good quality material such as sand or gravel that is easy to compact, strong, and relatively insensitive to moisture changes.

Geologic Applicability:

- Decreases the effects of soft clays, expansive clays, highly organic soils, topsoil, and uncontrolled fill.
- Shallow unsuitable soils, generally up to about 15 to 20 feet deep.
- Poorly graded aggregates are a good replacement material.
- Generally used above the groundwater table.

Construction Methods:

In Excavation and Replacement unsuitable material is removed and replaced by sand or gravel or recompacted cohesive soil. All highly compressible material in the load path should be excavated. Sand or gravel is the preferred backfill. On-site soils or borrow is more economical. Chemically stabilized soils are generally not free draining, and are not recommended for areas with a high groundwater table. The backfill is placed in lifts and compacted. Moisture sensitive soils should have a water content near optimum for compaction. Geosynthetic materials can be used to improve the behavior of the replacement fill.

Additional Information:

The depth of the excavation is determined by the depth of the unstable soil, which with groundwater and the soil's ability to support construction equipment dictates the type of construction equipment to use. Excavation construction equipment is readily available on most construction sites. The cost of the technology depends on the replacement material quality and availability. Cost generally can be $6 to $12 per cubic yard ($10 to $20/m2) of treated ground, but will vary with local and project conditions.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening
- Stabilization of pavement working platforms

Example Successful Applications:

- Considered as the baseline treatment approach for most projects.

Complementary Technologies:

Typically not used in conjunction with other technologies. Nontraditional replacement materials and compaction technologies can be used in conjunction. Replacement materials can be improved with reinforcing technologies.

Alternate Technologies:

Many SHRP2 R02 technologies can be alternates.

Potential Disadvantages:

- Requires excavation; hauling and disposal of materials; and hauling, placement and compaction of imported material versus in situ stabilization technologies.
- Often, but not always cost effective.
- Slower process than other technologies.
- Requires construction trafficking on exposed subgrade and replacement material, and may require dewatering, shoring, and/or disposal of waste materials.

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PREFABRICATED VERTICAL DRAINS WITH AND WITHOUT FILL PRELOADING

November 2012

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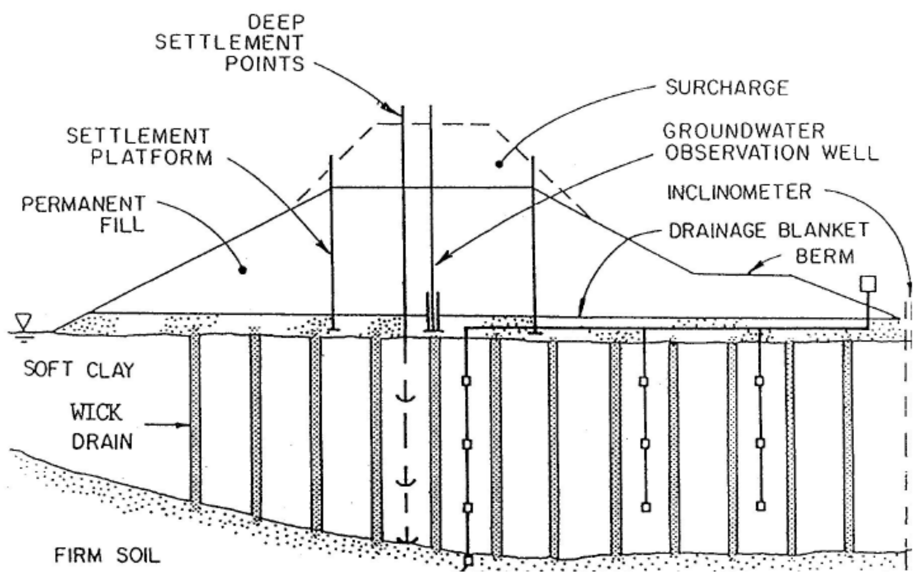

Schematic of a Prefabricated Vertical Drain Installation
(Figure from Elias et al. (2006))

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.

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:

- Embankment and roadway construction over unstable soils
- Roadway and 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 FHWA NHI-06-019.

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VACUUM PRELOADING WITH AND WITHOUT PVDS

November 2012

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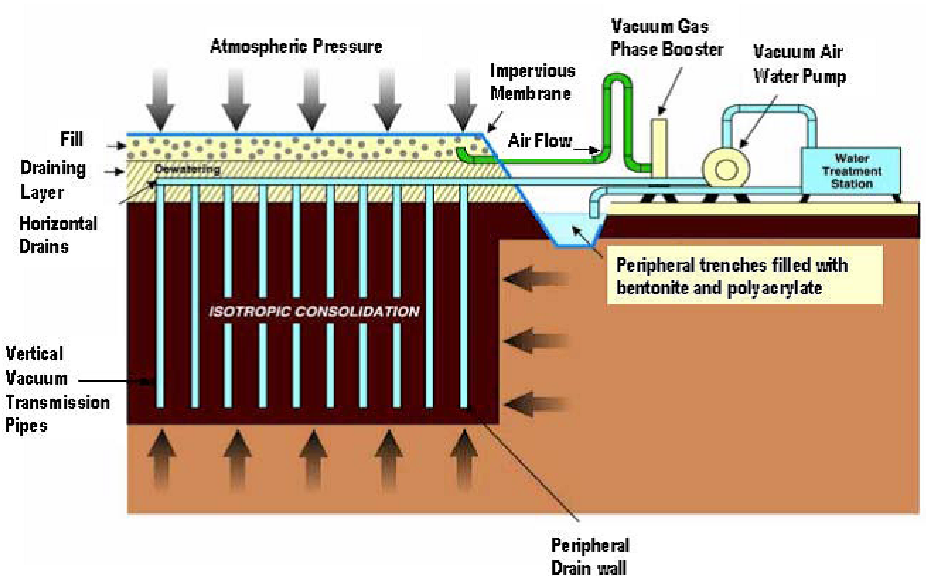

Vacuum Consolidation Process with PVDs
(Masse et al. 2001)

Basic Function

Vacuum Consolidation induces an increase in effective stress in foundation soils through reduction in pore pressures. Improves saturated soils by consolidation.

Advantages:

- No fill is required
- No staged loading is required
- No heavy equipment
- Environmentally friendly
- Established design methods and QC/QA requirements
- Cheaper and faster compared to surcharge loading

General Description:

Vacuum consolidation improves saturated soils by consolidation using a vacuum load to increase the effective stress in the foundation soils. Prefabricated Vertical Drains (PVDs) can be used to increase the effectiveness of the system by increasing the rate of consolidation.

Geologic Applicability:

- Compressible clays, soft, uniform clays.
- Has been known to improve sites with underlying clayey silt layers.
- More effective with shallow ground water table.
- Cannot be used to reduce secondary compression such as with high organic contents.

Construction Methods:

The soil site is covered by an airtight membrane. A dual venture and vacuum pump are used to create a vacuum at the site. Through a combination of dewatering and vacuum action, the water table is maintained at the base of the granular platform. Vacuum loads of about 12 psi (80 kPa) can be created and maintained. If greater loads are required for the soil, surcharge may be placed on top of the vacuum system. This method can be used with or without PVDs in the foundation soils. The PVDs will help increase the effectiveness of the method by accelerating the rate of consolidation. The PVDs should not be installed to the full depth of the soil to be consolidated if there is a more permeable lower layer below.

Additional Information:

The technology reduces the pore water pressure of the soil when the vacuum load is applied, causing the total stress to remain constant while the effective stress increases. Design methods and QC/QA requirements are well established and well documented case histories exist, but mostly for overseas projects. The cost of this technology is economical compared to excavation and fill and can be two-thirds of that of fill surcharge.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening
- Stabilization of pavement working platforms

Example Successful Applications:

- Oil Storage Station – Tainjin, China
- Highway Construction Site – Ambes, France

Complementary Technologies:

Typically not used with other technologies. Additional preloading by fill or water can be used. Has been used with dynamic compaction to help create excess pore pressure.

Alternate Technologies:

Deep foundation elements, sand drains, PVD with fill surcharge, electro-osmotic consolidation with PVDs, stone columns, grouting, deep soil mixing, excavation and replacement, and lightweight fill.

Potential Disadvantages:

- Maintenance of vacuum pressure.
- May cause cracks in surrounding soils.
- Vacuum pressure is limited to atmospheric pressure.
- Inward lateral movements from vacuum preloading can cause damage to adjacent structures.
- Vacuum pressure must be maintained for several months to obtain a high degree of consolidation.
- The system must be carefully monitored for leaks.
- Vacuum preloading is limited to providing an effective maximum surcharge of 14.5 psi (100 kPa).

Key References for this Fact Sheet:

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Technology Fact Sheet

SAND COMPACTION PILES

November 2012

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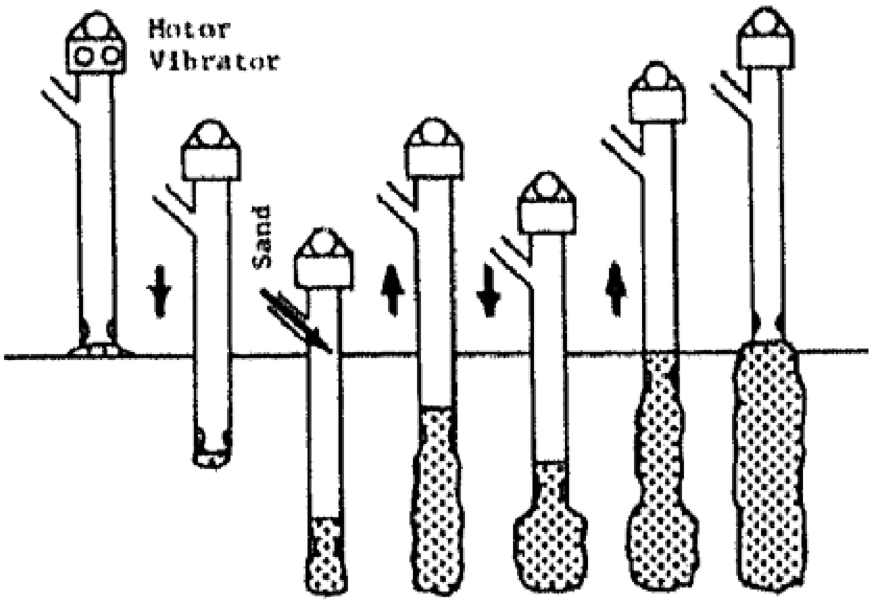

Construction Sequence for Sand Compaction Piles
(Figure from Barksdale (1987), after Tanimoto (1973))

Basic Function

Sand compaction piles are used to increase bearing capacity, prevent stability failure, reduce settlement, accelerate consolidation, and increase liquefaction resistance.

Advantages:

- Rapid construction, less risk of intrusion of soil into the pile (compared to stone columns),
- The hole is fully supported during construction preventing collapse
- Liquefaction prevention
- Settlement reduction.

General Description:

Sand compaction piles (or columns) are constructed by inserting sand into the ground through a pipe and compacting the sand by vibration, dynamic impact or static excitation to construct a compacted sand pile in soft ground. The sand pile and the surrounding soils are densified by the construction process. The principal concept for application to sandy soils is to increase the soil density by insertion of additional granular material into the ground. The principal concept for application to clay soils is reinforcement of the clay soil and provision of a drainage pathway.

Geologic Applicability:

- They can be installed in a wide range of soils, from soft clays to sandy soils.
- Have been installed up to 70 m deep and usually extend to a bearing stratum.

Construction Methods:

Sand compaction piles are installed by driving a pipe through loose sand or soft clay using a vibratory or non-vibratory method to densify loose sand and displace soft clay. After reaching a desired depth, the pipe is backfilled with sand. The sand pile and the surrounding loose soil are then densified by repeated penetration and extraction processes from the depth to the ground surface. In addition to sand, other granular materials, such as stone, construction waste, slags, oyster shells, and granulated coal ashes, etc. have been used. Sand compaction piles generally have diameters varying from 60 to 80 cm and they can reach up to 70 m in depth. The angle of internal friction of sand compaction piles typically ranges from 30° to 40° depending on the construction procedure.

Additional Information:

This technology is common in Asia, especially in Japan, for improvement of reclaimed land and foundations of embankments, railroads, quay walls, piers, breakwaters, tanks, etc. Specialty contractors are also available in the United States for this technology; however, only a few projects have been completed, mostly in California. Among these projects, other granular materials instead of sand have been mostly used. The design principles of sand compaction piles in loose sand are the reduction of void ratio and the corresponding increase of SPT N-value. The design principle of sand compaction piles in soft clay is based on composite foundations, which have higher composite moduli and shear strength values. The typical quality assurance method is the SPT method.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- Kansai International Airport Island Seawall Construction, Osaka Bay, Japan
- Hokkaido Highway Construction Project, Hokkaido, Japan

Complementary Technologies:

Sand compaction piles are generally a standalone technology. If there is a need for additional drainage, PVDs or other methods of drainage can be utilized.

Alternate Technologies:

Vibrocompaction, stone columns, aggregate piers, vibro-concrete Columns, deep dynamic compaction

Potential Disadvantages:

- Not commonly used in the United States
- Smearing effects when constructed in clay
- Greater replacement ratios are necessary compared to other columns (lower stiffness than other columns)
- Recent trends indicate a need for substitute materials due to rising costs and diminished availability of sand.
- Vibration and noise during construction

Key References for this Fact Sheet:

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AGGREGATE COLUMNS: AGGREGATE PIERS

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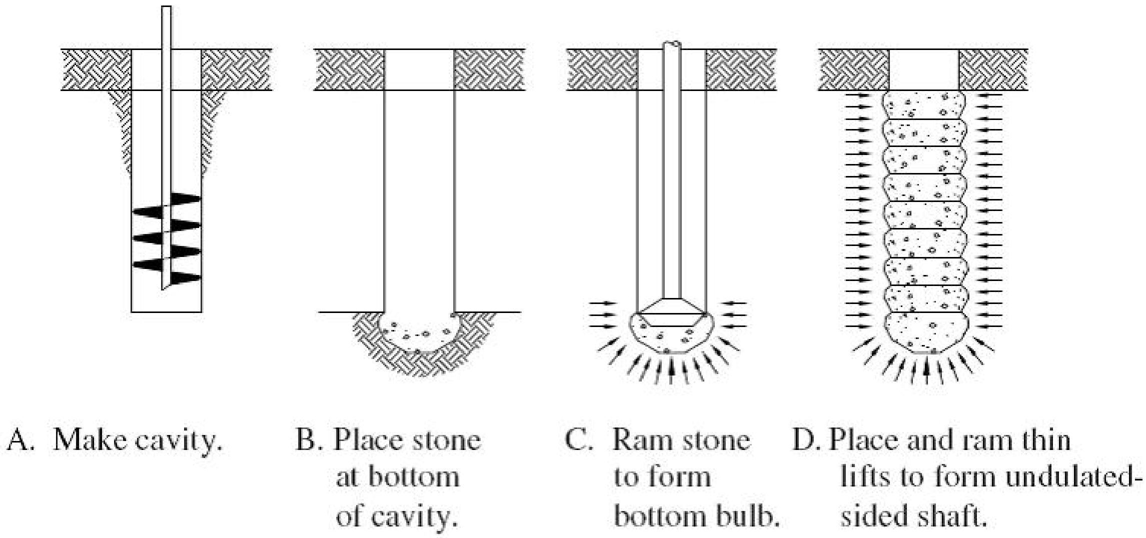

Aggregate Pier Construction Process.
(Figure from Collin (2007))

Basic Function

Aggregate Piers are a ground improvement method that uses compacted aggregate to create stiff pier elements. Aggregate Piers help increase bearing capacity, shear strength, rate of consolidation, and liquefaction resistance; and reduces settlement.

Advantages:

- Rapid installation
- Cost effective compared to other foundations options
- Creates additional drainage
- Allows for high level of compaction.
- Efficient QC/QA procedures

General Description:

Aggregate piers are a ground improvement system that places aggregate in predrilled holes to form stiff, high density aggregate piers. As the aggregate is rammed to form the piers, the aggregate is forced laterally into the sidewalls of the hole, partially densifying the surrounding soil.

Geologic Applicability:

- Soft organic clays, loose silt and sand, uncompacted fill, stiff to very stiff clays, and medium dense to dense sands.
- Elevated water tables and cohesionless soils complicate the installation.
- Can extend 7 to 30 feet (2 to 9 m) below grade.
- Construction may be difficult in soft clays and loose sands, necessitating casing of the borehole

Construction Methods:

24- to 36–inch (600 to 900 mm) diameter holes are drilled into the foundation soils. The holes normally reach depths of 7 to 30 feet (2 to 9 m) below grade. Casings are needed for cohesionless soils where the water table is above the depth of the pier. This lifts of well-graded aggregate are rammed into the holes. The first lift is open graded aggregate forms a bulb at the bottom of the pier. The subsequent compacted lifts are typically 12 inches deep. A high-energy beveled tamper mounted on excavator equipment is used to compact the aggregate. Design parameters include pier length, spacing, pier stiffness, and stress concentration ratio. Pier spacing is from 5 to 8 feet (1.5 to 2.5 m) center to center of the piers. Load capacities range from 50 to 100 kips (222 to 445 kN).

Additional Information:

Quality control operations consist of monitoring drill depth, number and thickness of aggregate lifts, compaction time per lift (normally 15 seconds), bottom stabilization tests, and dynamic cone penetration index tests. Quality assurance can consist of a full-scale load test to verify the design pier stiffness.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- Remediation of a Failed Slope – North Carolina
- Large Box Culvert Supported by Aggregate Piers – Iowa

Complementary Technologies:

Rammed aggregate piers are often used to support embankments, MSE walls, and reinforced slopes. with other technologies.

Alternate Technologies:

Site preloading, excavation and replacement, piles, stone columns, deep-mixing-method columns, jet grout columns and drilled piers.

Potential Disadvantages:

- Limited treatment depth.
- Lack of bending resistance.
- Difficult to install in clean sands when the groundwater table is above the bottom of the pier.
- Not applicable of wide heavy load applications.
- Usually only effective to a depth of 7 to 30 ft (2 to 9 m) below foundation.

Key References for this Fact Sheet:

Collin, J. G., (2007) “Evaluation of Rammed Aggregate Piers by Geopier Foundation Company Final Report” Technical Evaluation Report prepared by the Highway Innovative Technology Evaluation Center, ASCE, September 2007.

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AGGREGATE COLUMNS: STONE COLUMNS

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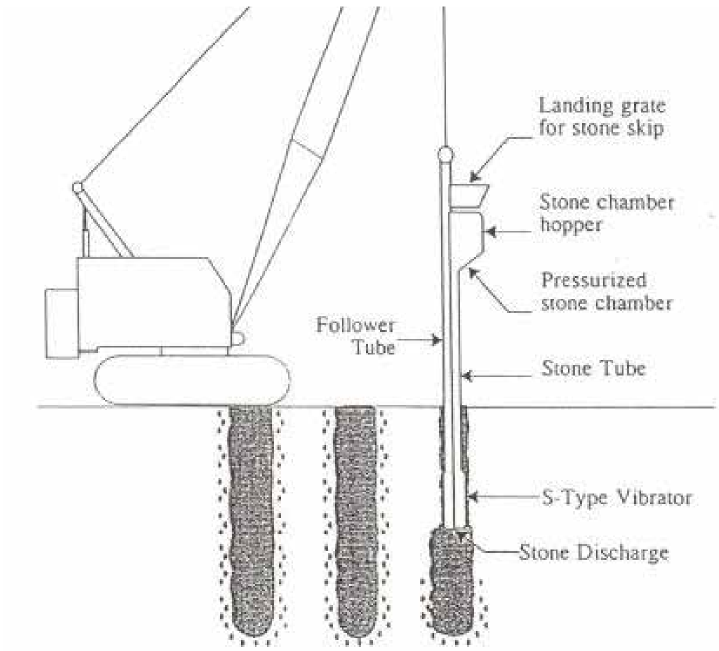

Bottom Feed Vibro Displacement
(Figure from Elias *et al.* (2006))

Basic Function

Stone Columns are a ground improvement method that uses compacted aggregate to create stiff pier elements. Stone Columns help increase bearing capacity, shear strength, rate of consolidation, and liquefaction resistance; and reduces settlement.

Advantages:

- Rapid installation
- Cost effective compared to other foundations options
- Creates an additional drainage path and accelerates consolidation
- Allows for high level of compaction.
- Efficient QC/QA procedures

General Description:

Stone Columns are columns formed with densified gravel or crushed rock in a pattern to create a composite foundation of the columns and the surrounding soil. The stiff columns carry a larger load than the surrounding soil to increase strength and capacity and reduce settlement.

Geologic Applicability:

- Improves clays, silts, and loose silty sands.
- Recommended in soft clays with an undrained shear strength greater than 400 psf but has been used in clays with a strength as low as 150 psf.
- Bulging columns is a concern in soft clays.
- Particle sizes and shape of the column infill material depends on the construction technique used, but generally ranged from ½ in to 3 in.
- Peat deposits can make the site unsuitable for stone columns.

Construction Methods:

Can be installed by water jetting, referred to as vibro-replacement or a wet, top feed method. Another method used is air jetting with dry, top and/or bottom feed method. In both methods, cylindrical vibrating probes are jetted into the ground to form holes, which are backfilled with gravel or crushed rock. Pre-augering can be used to reduce the ground displacement and vibration during construction. Depth of stone columns is normally between 20 and 30 feet with a limit of 90 feet. The rock is densified by the vibratory probes as they are withdrawn from the ground. Stone columns are placed in a triangular or rectangular pattern. The spacing and depth of the columns are determined by design standards.

Additional Information:

The vibro-replacement method has less displacement and vibration disturbance than the vibro-displacement method; however it creates a slurry in the process, creating more impact on the environment. Stone columns carry more load than the surrounding soils due to their greater stiffness. The stone columns and soil should be treated as a composite foundation. Stone columns cost about $15 to $20 per foot. Post improvement settlement ranges from 30% to 50%.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- Office Building – Missouri
- Slope Stabilization – New York

Complementary Technologies:

Stone columns have been used in conjunction with dynamic compaction to stabilize liquefiable soils at depths greater than those which could be treated by dynamic compaction alone.

Alternate Technologies:

Site preloading, excavation and replacement, aggregate piers, piles, deep-mixing-method columns, jet grout columns and drilled piers.

Potential Disadvantages:

- With the wet technique of installation, the jetting water must be disposed.
- Uncertain whether all stone reaches the bottom of the hole using the dry-construction method.
- Soft soils may not provide adequate lateral support for the columns.

Key References for this Fact Sheet:

Barksdale, R.D. and Bachus, R.C. (1983a). Design and Construction of Stone Columns Vol. I. FHWA/RD-83/026.

Barksdale, R.D. and Bachus, R.C. (1983b). Design and Construction of Stone Columns Vol. II. FHWA/RD-83/027.

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Technology Fact Sheet

VIBRO-CONCRETE COLUMNS

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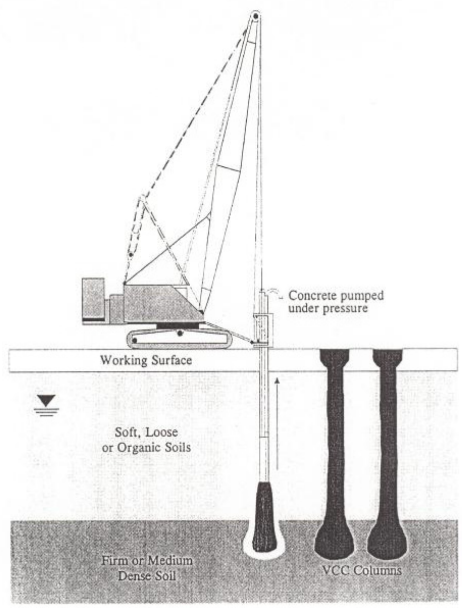


Diagram of Vibro Concrete Column Installation
(Figure from Elias et al. (2006))

Basic Function

Vibro-Concrete Columns (VCCs) are used to increase the bearing capacity of soft soils overlying stiffer strata. They are often used in combination with column supported embankments to reduce total and differential settlements.

Advantages:

- Reduced total, differential, and seismic settlements
- Greater column stiffness compared with aggregate columns
- Quick construction
- Environmentally friendly (no spoils)

General Description:

VCCs are similar to aggregate columns but use concrete in place of aggregate. They can be used in soft soils where aggregate columns are not appropriate. Typically, VCCs have an enlarged bottom and top bulb to increase end-bearing resistance and ensure adequate load transfer at the surface, respectively.

Geologic Applicability:

- Loose sands, soft clays, and organic soils.
- Most applicable in soft clay or peat with low undrained shear strength.
- Stiffer bearing stratum desirable at VCC tip.

Construction Methods:

VCCs use a vibrator to penetrate soft soils and to densify the bearing stratum to a limited degree. The column is constructed in a manner similar to stone columns but instead of feeding stone to the tip of the vibrator, concrete is pumped through an auxiliary tube to the bottom of the vibrator. As the vibrator is extracted from the ground, concrete is pumped to fill the void, creating a concrete column. During vibrator extraction, repenetration stokes are often used near the bottom and top of the column to form the enlarged bottom and top bulb. Typical column shaft diameters range from 18 to 24 inches and the enlarged base is usually about 24 inches or greater in diameter. Columns are generally spaced a minimum of 5 feet on center. Typical VCC lengths vary from 16 to 33 feet, though they can be installed to greater depths. The VCC is generally constructed without reinforcement; however, reinforcement can be included to support tensile and lateral loading. In axial compression, typical allowable design loads for VCCs range from 75 to 100 tons.

Additional Information:

VCC and similar technologies have been widely used on numerous projects worldwide. In current practice, VCCs are designed using modified driven pile or drilled shaft procedures. A design procedure developed specifically for VCCs still needs to be established. Despite the uncertainty in design, load tests and well-documented QC/QA can be used to validate performance and ensure consistency between columns.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils

Example Successful Applications:

- Bridge Approach Fill – Perth Amboy, NJ
- Roadway Embankment over Landfill – South of Hanover, Germany
- Railroad Embankment – Near Rancocas Creek, NJ

Complementary Technologies:

VCCs are often used with column supported embankments. Lightweight fills can be used to reduce embankments loads when necessary. Wick drains can be used to accelerate consolidation in compressible soils prior to VCC installation.

Alternate Technologies:

Excavation and replacement, vibrocompaction, aggregate columns, Combined soil Stabilization with Vertical columns (CSV), PVDs with or without fill preloading, continuous flight auger piles, driven piles, deep mixing methods, and jet grouting.

Potential Disadvantages:

- Lacks a well-established design procedure
- More expensive than aggregate columns

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.

Schaefer, V.R. (editor) (1997). Ground Improvement, Ground Treatment, Ground Reinforcement-Developments 1987-1997. Geotechnical Special Publication No. 69. ASCE, New York, 616 pp.

CONTINUOUS FLIGHT AUGER PILES

November 2012 http://www.GeoTechTools.org

CFA pile rig

Low Headroom CFA Pile Application

(Photographs from Brown et al. (2007))

Basic Function

Continuous Flight Auger piles (CFA) or Auger Cast-In-Place piles (ACIP) are a deep-foundation system to support loads.

Advantages:

- Rapid installation
- Limited installation noise and vibration
- Real time quality control
- May be effective in limited headroom conditions
- Low mobilization cost

General Description:

Pre-blended sand cement columns are installed into the ground using a rotary bored displacement technique. Soil is improved both by densification and load transfer mechanisms. CFA piles can be used for the support of bridges, bridge widening, sound wall foundations, columns support of embankments, and secant walls for lateral earth support.

Geologic Applicability:

- Medium to very stiff clay, cemented sand or weak limestone.
- Silty or clayey residual soils, with little cohesion.
- Medium dense to dense silty sands and well-graded sands.
- Stiff or cemented deposits overlying rock.
- Groundwater should be very deep.

Construction Methods:

In constructing the CFA, a hollow-stem auger is drilled into the ground to form the pile diameter. Sand-cement grout or concrete is pumped into the hole as the auger is removed to create a cast-in-place column. A steel bar reinforcement cage can be inserted into the column if required. The diameter of the column is generally 12 to 36 inches (0.3 to 0.9 meters). The depth can range from 60 to 70 feet (18.2 to 21.3 meters). Other techniques can displace the soil laterally using auger tools.

Additional Information:

CFAs can support lateral earth loads for critical and non-critical structures. Presence of a high groundwater table can lead to soil mining or necking in some soils. Reported production rates reached 1,500 feet per day per rig. Cost data is limited but prices are reported to be $12/lf or $20/lf for 12- to 18 inch diameter piles. Prices reached up to $60/lf to $80/lf for 30- to 36 inch piles.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- 52 Story Apartment Building - New York City
- FedEx MidAtlantic Hub - Greensboro, North Carolina

Complementary Technologies:

Column supported embankments with or without a load transfer mat.

Alternate Technologies:

Driven piles and drilled shafts. Micropiles when reinforcement of the pile is needed. Stone columns, aggregate piers, and vibro-concrete columns when reinforcement is not needed.

Potential Disadvantages:

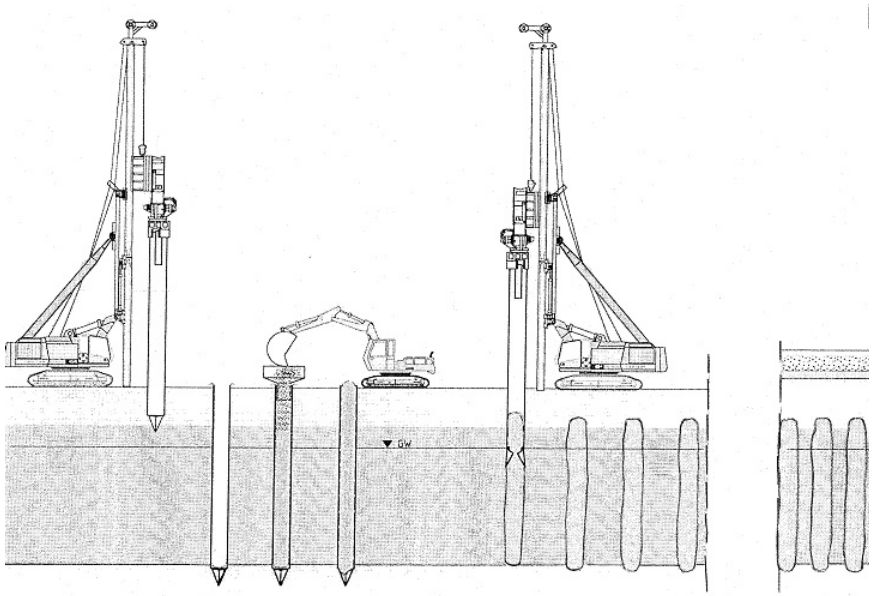
- Difficult to maintain proper rate of penetration.
- Not suited for soils with rocks and boulders.
- Relatively new technology.
- Procedures have not been fully developed.
- Problematic in soft soils, loose sands, clean uniformly graded sands under groundwater, voids, pockets of water, hard soil, or rock overlain by loose soil.

Key References for this Fact Sheet:

Brown, D.A., Dapp, S.D., Thompson, W.R. and Lazarte, C.A. (2007). "Design and construction of continuous flight auger piles." Geotechnical Engineering Circular (GEC) No. 8, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 270 p.

GEOTEXTILE ENCASED COLUMNS

November 2012 http://www.GeoTechTools.org



Construction of Geotextile Encased Columns with Displacement Method
(Raithel, M. and Henne, J., 2000)

Basic Function

Geotextile Encased Columns (GECs) stabilize the soil using a geotextile tube filled will with sand or gravel.

Advantages:

- Can be used in very soft soils where conventional stone columns are not effective or efficient
- Provide excellent vertical drainage, which may lead to more rapid construction due to dissipation of excess pore water pressure

General Description:

GECs were developed to overcome the problem of bulging of sand or stone columns installed in very soft soils, under vertical loading. The seamless geotextile casing around the column provides additional lateral confinement for the column needed in a very soft soil to carry vertical loads. GECs have been primarily used for embankment foundations with very soft clays (undrained shear strength less than 15 kPa) in Germany, Sweden, and The Netherlands since the 1990s.

Geologic Applicability:

- Geotextile encased columns are used to improve clays, silts and sands.
- GECs can be used in very soft soils with undrained shear strengths less than 15 kN/m2 where stone columns are not effective or efficient.

Construction Methods:

GECs can be installed in two ways: replacement or displacement. For the replacement method, an open steel pipe is driven into the ground and the inside soil is removed by an auger. For the displacement method, a steel pipe with two closed base flaps is vibrated into the ground and the soil around the pipe is displaced. Then, for both installation methods, the geotextile casing is lowered into the pipe and filled with sand or gravel. After the pipe is withdrawn under vibration out of the ground, a geotextile encased column with sand and or gravel at a medium density is completed. Compaction of the sand or gravel fill is achieved by gravity drop and further compaction occurs when the pipe is vibrated out of the ground at the end of installation.

Additional Information:

GECs have been used to increase bearing capacity, shear strength, and rate of consolidation, and to reduce settlement. Design of GECs is typically performed by determining the layout (triangular or rectangular), spacing, depth of columns, and the hoop stress in the geotextile to meet design requirements. The typical diameter of columns is 0.8 meters (32 inches) and the spacing ranges from 1.7 to 2.4 meters (5.5 to 8 feet) (i.e., 10 to 25% area replacement ratio). The design principle is similar to sand or stone columns in soft clays, i.e., treating a column and its surrounding soil in a unit cell as a composite foundation. Due to the encasement, the GECs are stiffer than conventional sand or stone columns installed in very soft soils.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- Railway Spur Roadbed, Oakland, CA
- Embankments, Vijfwal Houten, the Netherlands

Complementary Technologies:

Load transfer platforms

Alternate Technologies:

Preloading, stone columns, jet grouting, piles, and deep mixing methods

Potential Disadvantages:

- A proprietary technology
- Has not been widely used in the U.S. to date
- Seamless geotextiles, which require specialty manufacturing, are used for GECs.

Key References for this Fact Sheet:

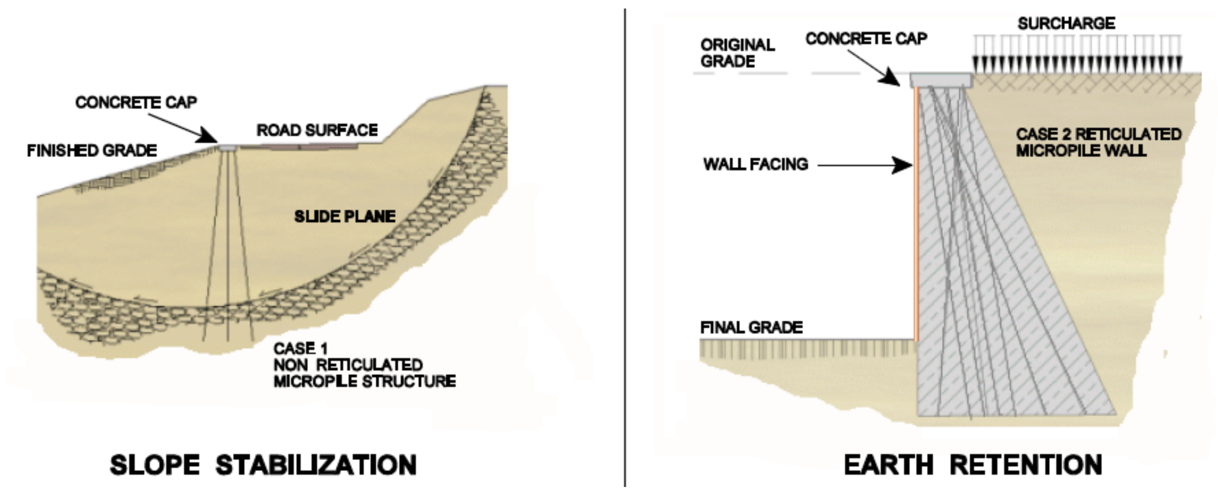
Alexiew, D., Brokemper, D., and Lothspeich, S. (2005). "Geotextile Encased Columns (GEC): Load capacity, geotextile selection and pre-design graphs." Contemporary Issues in Foundation Engineering, GSP No. 131, ASCE, Reston/VA: 1-14.

Elias, V., Welsh, J., Warren, J., Lukas, R., Collin, J. G., and Berg, R. R. (2006). "Ground Improvement Methods"-Volume I. Federal Highway Administration Publication No. NHI-06-020.

Raithel, M. and Kirchner A. (2008). "Calculation techniques and dimensioning of encased columns – Design and state of the art." Proceedings of the 4th Asian Regional Conference on Geosynthetics, Shanghai: 718-723.

MICRO-PILES

November 2012 http://www.GeoTechTools.org



(Figures from Sabatini et al. (2005))

Basic Function

Micropiles develop a load carrying capacity by means of a bond zone in soil, bedrock, or a combination of soil and bedrock.

Advantages:

- Can be drilled through all ground conditions at any angle
- Minimal disturbance to soil and adjacent structures
- Minimal noise disturbance during construction
- Smaller amount of spoils created than large diameter piles

General Description:

A micropile is a bored, grouted-in-place deep foundation element containing a steel reinforcing bar that develops its load carrying capacity by means of a bond zone in soil, bedrock, or a combination of soil and bedrock. Micropiles are small in diameter (typically < 12 inches) and typically at least 40% of the load is carried by the steel reinforcement and the remainder by the grout surrounding the bar. Due to their small diameter, micropiles develop axial capacity in skin friction due to the bond between the soil and grout and essentially have equal tensile and compressive capacities. Toe resistance is typically neglected. They can also accept lateral loads and can be designed to resist bending and shearing. Most are installed to depths less than 100 feet although micropiles have been installed to depths of 200 ft. Capacities routinely reach over 200 tons in soil and over 500 tons in rock.

Geologic Applicability:

- Can be installed in a wide variety of soil types and conditions.
- Suitable for sites with variable conditions such as boulders, buried utilities, and irregular lenses of competent and weak materials.
- Sites with karst and running sands are also viable for improvement by micropiles.

Construction Methods:

Drill rigs typically used for micropile installation are hydraulic rotary (electric or diesel) power units. They can be track mounted allowing for maneuverability on difficult and sloped terrain. Specialized drilling equipment is necessary for sites with low headroom (the equipment can be used in areas with less than 10 ft clearance). Otherwise, the same type of equipment used for ground anchors and grouting projects can be used for micropiles.

Additional Information:

Micropiles can be categorized by their behavior as either Case 1, where the micropiles are directly loaded to provide a structural support, or Case 2, where the micropiles are used to circumscribe and internally reinforce a coherent composite reinforced soil structure. Five different techniques exist for installation of the micropile based on the pressure of the grout, location of the packer, use of casing during construction, etc. As a result, the micropiles can be further classified depending on the method of grouting (A, B, C, D or E). The classification system consists of a two-part designation: a number, which denotes the micropile behavior, and a letter, which designates the method of grouting (e.g. Type 1D or Type 2C).

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- Littleville Landslide – AL
- Blue Trail Landslide, US HW 26-89 – WY
- Caltrans North Connector I 110 – Los Angeles CA

Complementary Technologies:

Can be used alone or with other technologies. Used with soil nails, ground anchors, grouting, and retaining walls.

Alternate Technologies:

Conventional driven piles, drilled shafts, underpinning pits, grouting, and ground anchors.

Potential Disadvantages:

- High slenderness ratio and their need for high levels of drilling expertise and contractor experience.
- Not suitable for soils where liquefaction is a concern, but the design can be adapted in certain situations.

Key References for this Fact Sheet:

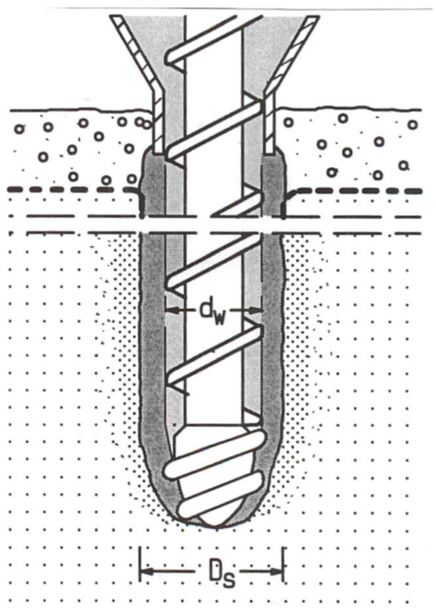
Bruce, D.A. and Juran, I. (1997). “Drilled and Grouted Micropiles: State of Practice Review, Volumes I, II, III, and IV.” Prepared for the Federal Highway Administration, Publication Nos. FHWA-RD-96-016. –017, -018, and –019, July.

Sabatini P.J., Tanyua, B., Armour, T. Groneck, P. and Keeley, J. (2005). “Micropile Design and Construction (Reference Manual for NHI Course 132078).” Federal Highway Administration, Publication No. FHWA-NHI-05-039, December 2005.

COMBINED SOIL STABILIZATION WITH VERTICAL COLUMNS

November 2012

http://www.GeoTechTools.org



CSV Installation Principle (dw = auger diameter, Ds = column diameter),
Scheller, P. and Reitmeier, W. (2001). "Combined Soil Stabilization with Vertical Columns (CSV): A New Method to Improve Soft Soils." Soft Ground Technology, GSP 112, ASCE, Reston, VA.

Basic Function

Combined Soil Stabilization with sand/cement Vertical Columns (CSV) is a ground improvement technique which densifies and transfers load through soft soils.

Advantages:

- Speedy installation
- No vibration during installation
- Soft organic soils can be treated
- No spoil is produced
- Lightweight equipment is used for installation
- Low cost relative to other technologies
- High flexibility in design and application

General Description:

Preblended sand/cement columns are installed into the ground using a rotary bored displacement technique. Soil is improved by densification and load transfer.

Geologic Applicability:

- Applicable to very soft to stiff cohesive soils, loose to medium cohesionless soils, and organic soils.
- Used to support embankments and structures.
- In loose sands, added benefit of densification of soil from installation process.
- Dewatering not required, groundwater levels are not connected to result of technology.
- Groundwater should hydrate the dry sand/cement mixture.

Construction Methods:

In constructing the CSV, preblended sand/cement columns are installed into the ground using a rotary bored displacement technique. The auger in the system rotates to the opposite direction of the drilling to displace the soil while the sand cement mixture is transported from a hopper down the flights of the auger. The sand and cement is a dry mixture that is hydrated using the moisture from the ground. Depths of columns can be 30 to 40 ft (9 to 12 m) with a 6 to 8 in (15 to 20 cm) diameter and an 8 to 10 in (20 to 25 cm) diameter top. Hydration and curing time should be considered and accounted for when determining schedules.

Additional Information:

The structural capacity of an 8 in (20 cm) diameter column is about 15 kips (67 KN). Where a low load capacity is needed, the CSV may be less expensive than other technologies.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- Old St. Augustine Road – Jacksonville, FL

Complementary Technologies:

Most applicable to column supported embankments used with or without geosynthetic reinforced load transfer platform.

Alternate Technologies:

Sand compaction columns, stone columns, rammed aggregate piers, vibro-concrete columns, continuous flight auger piles, geotextile encased columns, deep mixing methods, and jet grouting.

Potential Disadvantages:

- Low load capacity
- Requirement for groundwater to hydrate the dry sand/cement mixture
- Lack of simple, comprehensive, and reliable design procedure
- Lack of knowledge of technology benefits, design procedures, and construction techniques

Key References for this Fact Sheet:

DGGT AK2.8 (2002). "Merkblatt für die Herstellung, Bemessung und Qualitätssicherung von Stabilisierungssäulen zur Untergrundverbesserung: Teil I - CSV Verfahren (Combined Soil Stabilization with Vertical Columns)." Deutsche Gesellschaft für Geotechnik, Arbeitskreis 2.8

Kempfert, H. G. and Gebreselassie, B. (2006). "Excavations and Foundations in Soft Soils." Springer Berlin, Heidelberg. 461-523.

Technology Fact Sheet

GEOSYNTHETIC-REINFORCED CONSTRUCTION PLATFORMS

November 2012

http://www.GeoTechTools.org

Temporary and unpaved roads
(Courtesy of National Highway Institute)

Placement of geosynthetic in roadway
(Courtesy of Kansas Department of Transportation)

Basic Function

Geosynthetics are used as reinforcements in granular fill to form a temporary construction platform to support construction equipment and traffic over soft soil in order to avoid the formation of mud waves and excessive ruts. The contribution of the geosynthetic layer is to increase the local bearing capacity of soft subgrade.

Advantages:

- Advantages include its suitability for rapid renewal of transportation facilities, minimizing disruption of traffic
- Suitable for rapid renewal of transportation facilities
- Minimize disruption of traffic
- Reduce the risk of subgrade support problems
- Geosynthetics are not significantly affected by moisture
- Produce long-lived facilities for soft soil
- More economical than pile supported platforms for soft soil

General Description:

Design of geosynthetic-reinforced construction platforms is commonly based on local bearing capacity or slope stability. The contribution of the geosynthetic layer is to increase the local bearing capacity of soft subgrade. Several researchers have suggested different bearing capacity factors, Nc, for unreinforced, geotextile, and geogrid-reinforced unpaved roads. A single layer of geosynthetic is commonly used for unpaved roads.

Geologic Applicability:

- Geosynthetic-reinforced construction platforms may be used for soft subgrade with California Bearing Ratio (CBR) less than 3.
- Geosynthetics are used as reinforcements in granular fill to form a temporary construction platform to support construction equipment and traffic over soft soil in order to avoid the formation of mud waves and excessive ruts.

Construction Methods:

Surface of the subgrade was leveled to the targeted elevation and geosynthetics are laid directly on the subgrade soil in the machine direction parallel to the direction of trafficking with the required overlap and seamed as specified in the specification document. Drainage ditches are dug along each side of the road to provide drainage facility. The base course is placed in lifts and compacted to required degree of compaction at specified moisture content to provide desired grade.

Additional Information:

A single layer of geosynthetic is commonly used for unpaved roads. Slope stability analysis is generally adopted to evaluate the safety of heavy construction equipment (such as cranes) operated on soft soil. Current design methods for geosynthetic-reinforced unpaved roads are based on a single reinforcement layer placed at the interface between subbase and subgrade. In practice, however, multiple layers of geosynthetics are sometimes used. Development of design methods for multiple layer geosynthetic-reinforced unpaved roads is needed. Two-dimensional limit equilibrium methods are commonly used for designing geosynthetic-reinforced working platforms under heavy construction equipment. However, actual field conditions are most likely a three-dimensional problem.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening
- Stabilization of pavement working platforms

Example Successful Applications:

- Stabilization of unpaved roads with geosynthetics, Vancouver, British Columbia
- Reinforced haul-roads: Trials at Bothkennar, Scotland
- Reinforced road base, Monroe, LA

Alternate Technologies:

Chemical stabilization soil, excavation and replacement, use of high-quality pavement materials, geotextiles with geogrid, pile supported platforms.

Potential Disadvantages:

- Lack of an acceptable method to evaluate the difference between geosynthetic products and to design multiple layers of geosynthetics.
- Lack of a reliable AASHTO design method
- Lack of demonstration of life cycle cost benefits

Key References for this Fact Sheet:

Fannin, R.J. and Sigurdsson, O. (1996). “Field observations on stabilization of unpaved roads with geosynthetics.” Journal of Geotechnical Engineering, Vol. 122, No. 7, 544-553.

Holtz, R.D., Christopher, B.R., and Berg, R.R. (2008). “Geosynthetic design and construction guidelines.” U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., FHWA-HI-07-092.

Kim, W., Edil, T.D., Benson, C.H., and Tanyu, B.F. (2005). “Structural contribution of geosynthetic-reinforced working platforms in flexible pavement.” Transportation research Record 1936, National Research Council, 43-50.

Technology Fact Sheet

DEEP MIXING METHODS

November 2012 http://www.GeoTechTools.org

Equipment Installing a Block-Type Deep Mixing Pattern
(Figure from Elias et al. (2006))

Basic Function

Deep mixing refers to the blending of cement, lime, slag, or other binders in powder or slurry form to stabilize soil in-situ. Methods increase strength and decrease compressibility.

Advantages:

- Can be used in noise and vibration sensitive areas
- High production capacity
- Applicability to on-land and marine projects
- Applicable in a large range of soil types
- Relatively easy installation procedure
- Dewatering is not required
- Can be economical on large projects

General Description:

Binders in powder or slurry form are mixed into soil using rotating tools, chainsaw like mixing equipment, mixing probes or other devices. When the binder is in powder form, the method is commonly referred to as the dry method. When the binder is in slurry form, the method is commonly referred to as the wet method. The choice of application method will depend upon the characteristics of a particular site and the desired performance characteristics of the treated soil.

Geologic Applicability:

- Suitable in soils that can be stabilized with cement, lime, slag, or other binders.
- Not suitable in soils with large cobbles or boulders.

Construction Methods:

Mixing can be done with single-axis rotating tools to create single columns, multiple-axis rotating tools to create a set of overlapping columns in a single stroke, chainsaw-like mixing equipment to create continuous panels, mixing probes for mass stabilization, or other devices. For dry- and wet-method rotary mixing tools, binders are injected through the hollow stem of the rotating tool. Dry method columns are usually 2 to 3 ft (0.6 to 0.9 m) in diameter and less than 60 ft (18.3 m) deep. Wet method columns can be up to 8 ft (2.4 m) in diameter and are usually less than 100 ft (30.5 m).

Additional Information:

Deep mixing methods can be less expensive than excavation and replacement since the in-situ soil is used. Cost is increased by high mobilization and demobilization costs from the large machines so this method is not suited for smaller projects. The wet method produces spoil where the dry method is environmentally friendly and does not produce spoil.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- I-95/ Route 1 Interchange Test Embankment – Alexandria, VA
- I-15 – Utah
- Cypress Permanent Replacement Project – Oakland, CA
- Oil Storage Tanks – Lafourche Parish, Louisiana

Complementary Technologies:

Lightweight fills for embankment construction and deep mixed columns for column supported embankments.

Alternate Technologies:

Other olumn technologies; for construction on soft soils, removal and replacement, vacuum or traditional preloading and prefabricated drains.

Potential Disadvantages:

- The wet method requires large and heavy mixing rigs with large headroom and may be too heavy for softer soils.
- A simple, comprehensive, and reliable design procedure is not available.
- Lack of widely recognized quality assurance program.
- High cost for mobilization and demobilization.

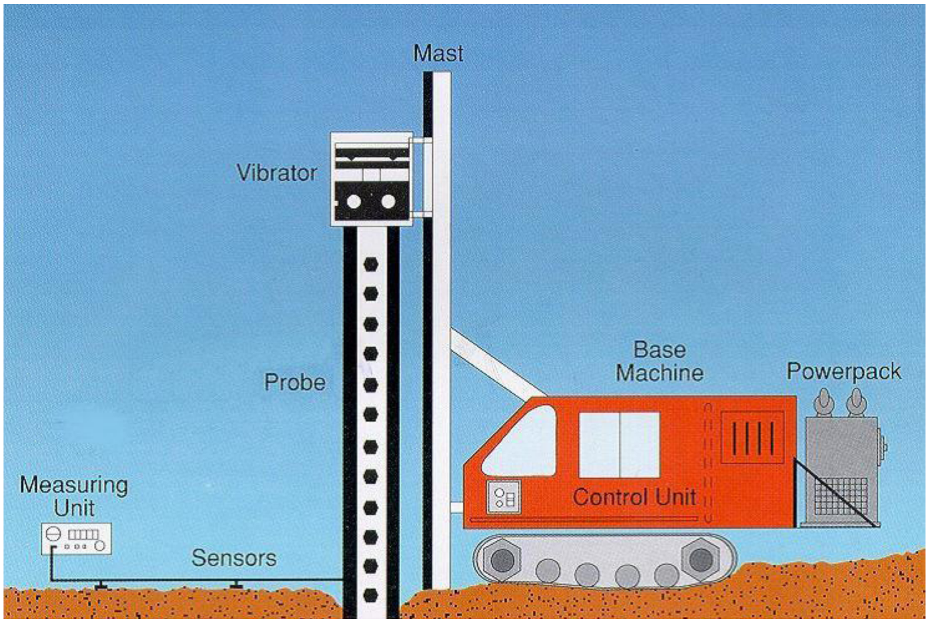
Key References for this Fact Sheet:

Elias, V., Welsh, J., Warren, J., Lukas, R., Collin, J. G., and Berg, R. R. (2006). "Ground Improvement Methods"-Volume I. Federal Highway Administration Publication No. NHI-06-020.

Bruce, M.E.C., Berg, R.R., Collin, J.G., Filz, G.M., Terashi, M., and Yang, D.S., (2012). FHWA Design Manual: Deep Mixing for Embankment and Foundation Support, (publication pending).

VIBROCOMPACTION

November 2012 http://www.GeoTechTools.org



Main Elements of Vibratory Compaction Equipment
(after Massarch and Fellenius 2005)

Basic Function

Vibrocompaction densifies deep cohesionless soils to increase bearing capacity, increase shear strength, reduce settlement, and increase liquefaction resistance.

Advantages:

- More economical and faster construction than deep foundations
- Many case histories in United States
- Effective above and below water table

General Description:

Vibrocompaction is a method of deep densification. It can be used on cohesionless soils through penetration and vibration of a probe to densify the surrounding soil.

Geologic Applicability:

- Cohesionless soils.
- Applicable soils include clean sands with less than 15% silts and/or less than 2% clay.
- Typical depths range from 10 to 50 feet (3 to 15 meters).
- Range may be as low as 3 feet (1 meter) and as deep at 120 feet (37 meters).

Construction Methods:

Vibrocompaction is performed using the penetration and vibration of a probe to rearrange soil particles into a denser state. The design includes the layout of triangular or rectangular grid points, the spacing of the grid points, and the depth of vibrocompaction. Typical spacing of grid points range from 5 to 15 feet (1.5 to 5 meters) depending on the soil type, the density of the soil, and the soil density goal. Typical depth of vibrocompaction ranges from 10 to 50 feet (3 to 15 meters). Sand can be backfilled into the craters to maximize the densification, but in many instances, is not. During insertion and extraction of the probe, the frequency of vibration should be greater than 30 Hz to decrease shaft resistance. During the compaction phase, the frequency is generally between 15 and 20 Hz. The probe should be inserted to the required depth as quickly as possible at a high frequency. Then, the soil is compacted at the resonance frequency, followed by removing the probe quickly at a high frequency. SPT and CPT results help determine the final density achieved, as well as strength, deformation, and liquefaction resistance. Design charts are available in the literature.

Additional Information:

Vibrocompaction can be more cost efficient than excavation and replacement and deep foundation systems. The compactibility of the soils at the site can be evaluated before vibrocompaction based on soil grain size analyses and the SPT and CPT resistances. Vibrocompaction can increase the angle of internal friction by 5 to 10 degrees.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- Wando Terminal Port – Charleston, SC
- I-90 Mt. Baker Ridge – Seattle, WA
- Manchester Airport – NH

Complementary Technologies:

Generally used alone. Prefabricated vertical drains can be used to speed up consolidation and drainage.

Alternate Technologies:

Sand compaction piles, deep dynamic compaction, aggregate columns, vibro-concrete columns

Potential Disadvantages:

Narrow range of soils that the method can improve. Noise and vibration. Contractor experience is critical. Quality control should be carefully monitored.

Key References for this Fact Sheet:

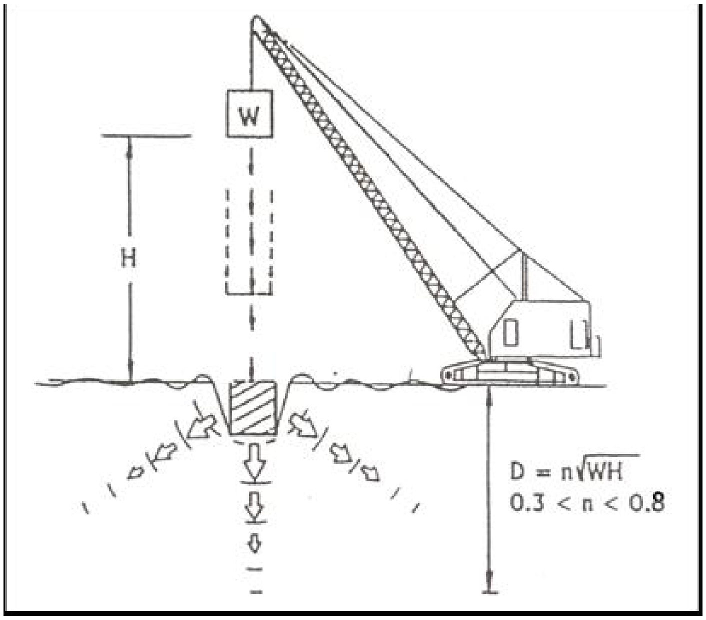
Elias, V., Welsh, J., Warren, J., Lukas, R., Collin, J.G., and Berg, R.B. (2006). "Ground Improvement Methods-Volume I." Federal Highway Administration, FHWA NHI-06-019.

Massarsch, K.R. and Fellenius, B.H. (2001). "Vibratory compaction of coarse-grained soils." Canadian Geotechnical Journal, Vol. 39, No. 3, 25p.

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

DEEP DYNAMIC COMPACTION

November 2012 http://www.GeoTechTools.org



Schematic of Dynamic Compaction
(after Lukas (1995))

Basic Function

Deep Dynamic Compaction (DDC) densifies marginal materials using high levels of impact energy at the surface.

Advantages:

- Suitable for many types of soils with less than 15% fines
- Low cost for large area of improvement
- Ability to measure improvement
- Many available contractors
- Simple equipment
- Produces relatively uniform compressibility

General Description:

DDC applies energy by raising and dropping a tamper (weight) repeatedly from a height of 30 to 120 feet. The energy densifies the soil to depths that increase with the magnitude of the energy. The ground surface is then compacted with a smaller, broader tamper or conventional compaction equipment.

Geologic Applicability:

- Loose pervious and semi-pervious soils with fines contents less than 15%
- Materials containing large voids
- Soil improvement to a maximum depth of about 30 to 35 feet
- Not recommended for silty or clayey soils
- Effective in soils above or below the groundwater table (Note: Water table should be 6 feet below grade; fill can be placed above a high groundwater site to achieve this distance.)

Construction Methods:

A tamper with a weight of 5 to 40 tons is dropped using a crane from a height of 30 to 120 feet. The tamper is dropped in a systematically controlled pattern on a coordinate grid layout. The impacts are spaced at a distance depending on the depth of the compressible layer, the depth to the groundwater, and grain size distribution. Five to 15 blows per grid point are applied. The first phase is the high-energy phase to improve the deeper layers. This is followed by a low-energy phase to densify the upper layers. In the low-energy phase, the tamper is only raised 15 to 20 feet. Backfilling the craters and additional passes may be required.

Additional Information:

Proximity of groundwater or excessive crater depths limit the number of blows at each grid point. In saturated soils with some fines (less than 15% fines), the compaction may create excess pore water pressure that reduces the effectiveness of compaction unless the pressure is dissipated. DDC is more economical than other technologies for large area ground improvements.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- Densification of Loose Pockets & Voids – FL
- Study Site – Charleston, SC

Complementary Technologies:

Prefabricated vertical drains (without fill preloading) to dissipate pore water pressures and permit densification of soils with higher fines content

Alternate Technologies:

Excavation and replacement, sand compaction columns, vibrocompaction, blasting densification, aggregate columns, and deep foundation systems.

Potential Disadvantages:

- Mobilization costs
- Large ground vibrations and lateral displacements
- Limited effective treatment depth
- Some safety concerns

Key References for this Fact Sheet:

Elias, V., Welsh, J., Warren, J., Lukas, R., Collin, J. G., and Berg, R. R. (2006). "Ground Improvement Methods-Volume I." Federal Highway Administration Publication No. NHI-06-020.

Lukas, R.G. (1986). "Dynamic Compaction for Highway Construction Volume I: Design and Construction Guidelines." U.S. Department of Transportation, Federal Highway Admin., Washington, D.C., FHWA/RD-86/133.

Lukas, R.G. (1995). "Dynamic Compaction – Geotechnical Engineering Circular No. 1", U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., FHWA-SA-95-037.

RAPID IMPACT COMPACTION

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(Photograph from Kristiansen and Davies (2004))

Basic Function

Rapid Impact Compaction (RIC) provides controlled impact compaction to reduce settlement and improve geotechnical properties including stiffness and bearing capacity.

Advantages:

- More efficient use of energy to compact soil than deep dynamic compaction
- High quality of compaction in terms of degree and uniformity
- Versatility of movement of equipment
- Can be used close to existing structures
- Small foundation areas can be treated

General Description:

RIC uses equipment mounted on an excavator that drops a weight to densify soils to a depth dependent on the groundwater, soil properties, and compaction energy. This technique is generally used on granular soils to improve the geotechnical properties and reduce settlement.

Geologic Applicability:

- Technique is suited for a wide variety of granular soils and fills such as ash fills, waste fills and building wastes
- Not recommended for weak, low permeability soils with a high moisture content, for clayey soils and fills, or soils with high fines contents
- Effectiveness is dependent on soil properties such as degree of saturation, moisture content, and plasticity
- Groundwater may reduce densification if soil cannot drain. Groundwater level is recommended to be at least 3 feet (1 meter) below surface. Sump pump may be needed

Construction Methods:

RIC is typically used to improve the geotechnical properties of granular fills and to reduce settlement. RIC has also been used in collapsible soils, ash fill, waste fill, and building waste. A 5 to 9 ton weight (4.5 to 8 tonne) is mounted on excavator equipment and is dropped about 4 feet (1.2 meters) on a 5-foot (1.5-meter) diameter tamper capable of imparting 40 to 60 blows per minute. The resulting force of this RIC process densifies soils to depths of 10 to 20+

feet (3 to 6 meters). Depth of compaction is dependent on compaction energy level, soil properties, and groundwater conditions. The higher the energy level, the greater the depth of compaction. Approximately 9,000 to 30,000 SF (800 to 2500 m2) can be covered in an average single-shift day.

Additional Information:

Quality control is performed by monitoring the compaction energy and deflection of the soil on each blow. Quality assurance is performed by recording the before and after results of the SPT N-value or CPT cone resistance until the required results are met for the zone needing improvement. Plate bearing tests have been used for different field trials to evaluate bearing characteristics. Peak noise levels have been recorded to be 88 dBA.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- Pasco Middle School Building EE – Land O'Lakes, FL
- Tampa Terminal Tank 6 – Tampa, FL
- Naval Square Biddle Hall Annex and Townhomes – Philadelphia, PA

Complementary Technologies:

Intelligent compaction

Alternate Technologies:

Deep dynamic compaction, vibroflotation, stone columns, compaction grouting, excavation and replacement

Potential Disadvantages:

- The depth of compaction cannot be controlled.

Key References for this Fact Sheet:

Serridge, C.J. and Synac, O. (2006). "Application of the Rapid Impact Compaction (RIC) technique for risk mitigation in problematic soils." Proceedings of IAEG2006, London, Paper No. 294.

Simpson, L.A., S.T. Jang, C.E. Ronan and L.M. Splitter (2008) "Liquefaction Potential Mitigation using Rapid Impact Compaction." Proceedings of the Conference of Geotechnical Earthquake Engineering and Soil Dynamics IV, Sacramento, CA, Paper No. 181.

Kristiansen, H. and Davies, M. (2004), "Ground Improvement Using Rapid Impact Compaction", Proceedings from the 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, Paper No. 496.

HIGH ENERGY IMPACT ROLLERS

November 2012 http://www.GeoTechTools.org

Landpac 25-kJ Three-Sided Impact Roller
(Photograph courtesy of Landpac® (www.ladnpac,co,uk)

Basic Function

High energy Impact Roller (IR) technology transfers high-impact compaction energy to densify/rubblize in-situ materials.

Advantages:

- Subgrade can be improved from the surface without overexcavation and replacement
- Can crush rock/concrete into rubble
- Can compact thick soil lifts and thus increase compaction productivity
- Achieves high density

General Description:

High energy impact roller technology uses a lifting and falling motion to compact the soil. The roller is pulled at high speeds, 6 to 7.5 mph (10 to 12 km/h), to generate a high impact force that densifies materials. IRs can densify existing fill, collapsible sands, landfill waste, mine haul roads, and bulk earthwork. It can also be used to rubblize existing pavement to create a new subbase.

Geologic Applicability:

- Suitable for a wide variety of materials: clays, silts, sands, rocks/boulders, dredged fill, and industrial waste.
- Compaction improvement depth depends on the type of material and stratigraphy, but can be as much as 16.4 feet (5 meters) and generally up to 6.6 feet (2 meters).

Construction Methods:

High energy impact roller technology uses non-circular shaped tow-behind solid steel molds.

Additional Information:

Impact rollers can densify materials to depths greater than conventional static or vibratory rollers. A recent development in the IR technology is Landpac's Continuous Impact Response (CIR) system. The CIR system involves instrumenting the IR drum with an accelerometer and continuously monitoring the decelerations (in g's) integrated with a Global Positioning System (GPS) and presenting the results as a map in real-time to the operator.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening
- Stabilization of pavement working platforms

Example Successful Applications:

- Doha International Airport, Qatar
- Reconstruction of the Trans Kalahari Highway, The Republic of Botswana, Africa
- The Port River Expressway, Adelaide, Australia
- Port Coogee Marina Project, Western Australia

Complementary Technologies:

Intelligent compaction and traditional compaction

Alternate Technologies:

Deep foundations, deep dynamic compaction, stone columns, compaction grouting, excavation and replacement, rapid impact compaction

Potential Disadvantages:

- The upper 4 to 6 inches (100 to 150 mm) of the surface is disturbed/shattered.
- Small sites with complex geometries limit the driving speeds, and it may not be possible to densify all areas.
- Vibrations may affect nearby structures.

Key References for this Fact Sheet:

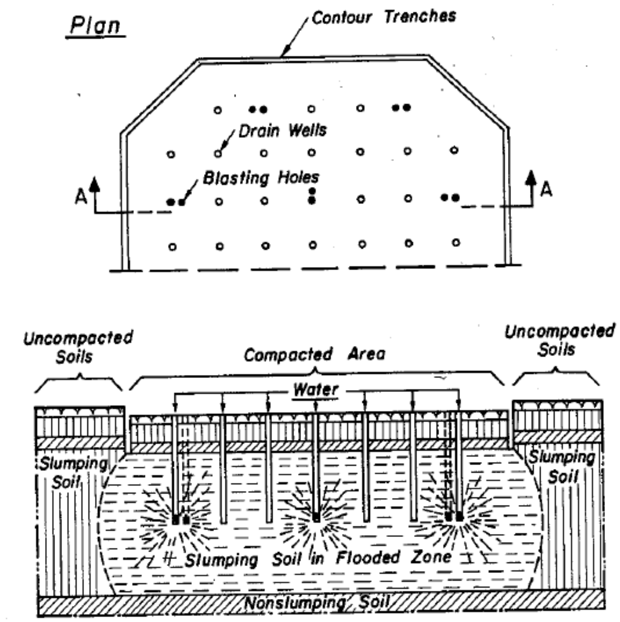
Clegg, B., and Berrangé, A.R. (1971). "The development and testing of an impact roller," Trans. S. Afr. Instn. Civ. Engs. Vol. 13, No. 3, pp. 65-73.

Avalle, D.L. (2007). "Trials and validation of deep compaction using the "square" impact roller." Australian Geomechanics Society Sydney Chapter Mini-Symposium: Advances in Earthworks, 17 October, Sydney, Australia.

Pinrad, M.I. (2001). "Development in compaction technology", Geotechnics for Roads, Rail Tracks, and Earth Structures, Edited by Correia, A.G., and Brandl H., A.A. Balkema Publishers, The Netherlands.

BLAST DENSIFICATION

November 2012 http://www.GeoTechTools.org



Mitchell, J.K. (1981). "Soil Improvement-State of the art report." Proceedings of 10th IC-SMFE. Stockholm, Vol. 4, pp 509-565.

Basic Function

Blast densification (explosive compaction) densifies loose, relatively clean, saturated, cohesionless soils by liquefying the soil and consolidating.

Advantages:

- Ability to treat deep soils
- Rapid technique
- Inexpensive
- Successful under a variety of climate and environmental extremes

General Description:

Detonation of explosives induces liquefaction of the soils, which consolidate to a denser, more stable configuration due to the vibrations and force from the blast and gravity. Blast densification reduces effects of long-term settlement and improves the foundation soil strength.

Geologic Applicability:

- Best suited for loose, relatively clean, saturated cohesionless soils
- Has been used to treat soils up to depths of 130 feet
- Maximum effective depth has not been defined
- Has been used on saturated alluvial deposits, hydraulic fills, and volcanic debris flows

Construction Methods:

Charges are placed in pre-drilled or jetted holes that are located in a grid pattern with charge spacings typically between 10 and 50 feet (3 to 15 meters). Several charges are fired at once, with delays between charges to enhance cyclic loading while minimizing peak acceleration. Often multiple passes of charges are required to reach the desired densification. The vertical spacing of the charges varies with the size of the charges and thickness of the layer to be densified. The size of the charge is based on empirical design equations, the single-pass grid spacing, and vibration constraints. Denser soils require larger charges to break down the soil structure.

Additional Information:

Volume reductions of 4 to 10% and relative density increases from 10 to 40% have been measured. Blast densification helps achieve long-lived projects by increasing foundation soil stability and strength and reducing the settlement over an extended period of time. The cost of the technology is relatively inexpensive compared to other technologies. This technology has not been widely used to date, but it is a proven technology that can provide rapid and cost effective construction.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils

Example Successful Applications:

- National Geotechnical Experimentation Site – Treasure Island, San Francisco, CA
- Blast Densification Field Study – South Carolina
- Highway 504 Bridge over Coldwater Creek – Mt. St. Helen's, WA

Complementary Technologies:

Blast technology is often used as a stand-alone method. It can be used to treat the deep soils while another technology is used for the surface soil.

Alternate Technologies:

Deep dynamic compaction, sand compaction piles, vibrocompaction, or other mechanical ground improvement techniques.

Potential Disadvantages:

- Lack of validated theoretical design procedures
- Improvement may be time dependent
- Surface heave may occur
- Limitations on how much densification can be obtained
- Difficulties in placing large charges at great depths
- Oversized charges may cause cratering of the ground surface, slope failure, or vibration related damage.

Key References for this Fact Sheet:

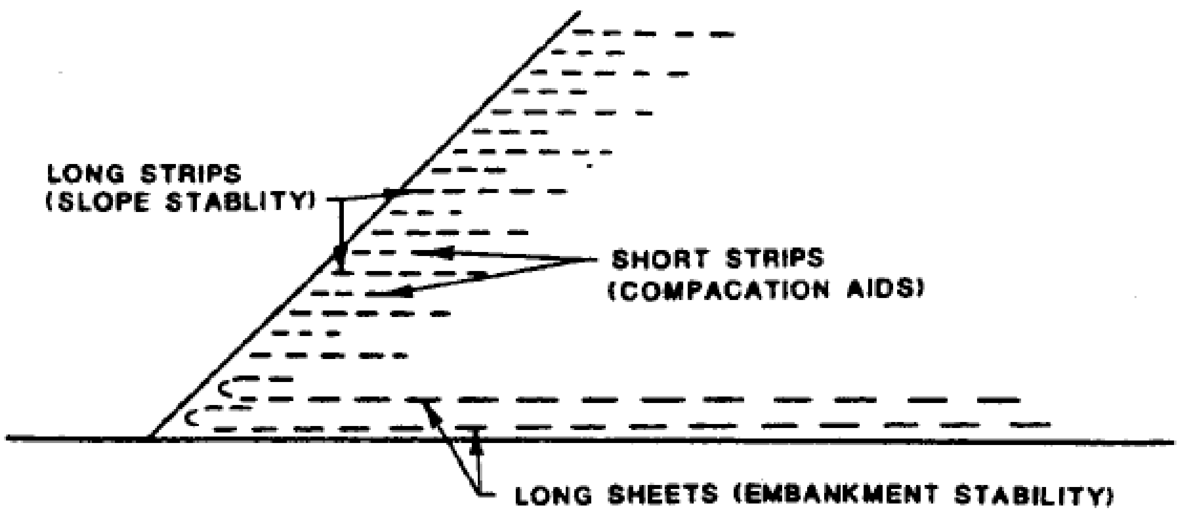
Ivanov, R.L. (1967). Compaction of Non Cohesive Soils by Explosions (translated from Russian), National Technical Information Service Report No. TT 70-57221, U.S. Dept. of Commerce, Springfield, VA, 211 pp.

Narin van Court, W.A. and Mitchell, J.K. (1994). "Soil improvement by blasting: part I." Journal of Explosives Engineering, Vol. 12, No. 3, pp. 34-41, Nov./Dec.

Narin van Court, W.A. and Mitchell, J.K. (1995). "Soil improvement by blasting: part II." Journal of Explosives Engineering, Vol. 12, No. 4, pp. 26-34, Jan./Feb.

REINFORCED SOIL SLOPES

November 2012 http://www.GeoTechTools.org



Slope Reinforcement using Geosynthetics
(Figure from Christopher et al. 1990)

Basic Function

Reinforced soil consists of soil reinforcements added to natural soil body alternating with compaction efforts applied to form a composite which containing a improved strength and stability versus the initial soil state.

Advantages:

- Uses simple and rapid construction procedures
- Eliminate wall facing elements
- Less required right of way
- Less filling materials or ROW than flatter, unreinforced slopes
- Vegetated-faced soil slopes landscaped to blend with natural environment

General Description:

Reinforced Soil Slopes (RSSs) are a form of mechanically stabilized earth that incorporates planar reinforcing elements in constructed earth-sloped structures with face inclinations less than 70º from the horizontal (MSE structures with face inclinations > 70º are classified as walls). Multiple layers of geogrids, geotextiles, steel welded wire mats, or woven steel mats may be placed in an earthfill slope during construction to reinforce the soil and provide a stable, sloped faced earth retention structure, as shown in Figure above.

Geologic Applicability:

- RSSs can be constructed over any firm foundation or pre-treated subgrade surface, which shall be level, uniform, and also free from deleterious materials, loose and/or otherwise unsuitable soils.
- Any soft areas as predetermined by engineers shall be excavated or replaced with suitable compacted soils.

Construction Methods:

The construction of RSSs is very similar to normal slope construction. First, site preparation should be conducted to treat the subgrade soil prior to the first level of reinforcement placement. Second, in reinforcement layer placement stage, the reinforcement shall be well secured by retaining pins to prevent movement from filling and compaction process. Third, the well-designed backfill soil shall be placed on the top of flatted reinforcement to form a lift with minimum thickness of 6 inches. Fourth, compaction should be applied on placed backfill layer to achieve designed compacted density and moisture content. Step two to Step four are repeated until the desired slope height is reached. Then, the surface drainage features and slope treatment are added at completion of the reinforced slope.

Additional Information:

Mechanically stabilized earth slopes, i.e. RSSs, have been used by state highway agencies since the early 1980s. The use of RSS structures has expanded dramatically in the last two decades, and it is estimated that several hundred RSS structures have been constructed in the United States. Currently, 100 to 150 RSS projects are being constructed yearly in connection with transportation related projects in the United States, with an estimated projected vertical face area of 2,000,000 ft2/year (190,000 m2/year). Significantly more RSS projects are designed and constructed yearly for private (non-transportation) works.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- The Dickey Lake Roadway Grade Improvement Project – Northern Montana
- Salmon-Lost Trail Roadway Widening Project – Idaho
- Pennsylvania SR 54 Roadway Repair Project – Pennsylvania

Complementary Technologies:

RSS can be used with Column Supported Embankments and MSE walls

Alternate Technologies:

MSE walls, conventional unreinforced slopes

Potential Disadvantages:

- Generally limited to firm foundation sites.
- Relatively large space needed to install required reinforcement.
- Project specific or regionally specific erosion control design and detailing for steepened slope face

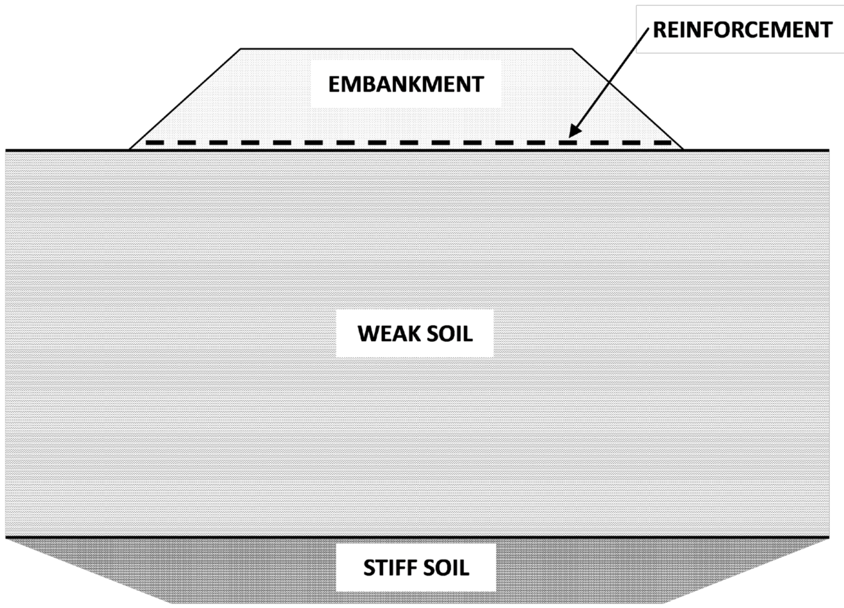
Key References for this Fact Sheet:

Berg, R.R, Christopher, B.R, and Samtani, N.C (2009). Design of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., FHWA-NHI-09-083, 622 p.

Christopher, B.R., Gill, S.A., Giroud, J.P., Juran, I. Scholsser, F., Mitchell, J.K. and Dunnicliff, J., (1990). "Reinforced Soil Structures, Volume I. Design and Construction Guidelines", U.S. Department of Transportation, Federal Highway Administration, Washington DC, Report No. FHWA-RD--89-043, 287 p.

GEOSYNTHETIC REINFORCED EMBANKMENTS

November 2012 http://www.GeoTechTools.org



Embankment on Weak Foundation
(After Bonaparte and Christopher (1987))

Basic Function

Geosynthetic reinforced embankments stabilize embankments constructed on soft soils by means of horizontal layers of high-strength geosynthetics. The reinforcement placed at the base of the embankment and used to increase stability and resistance to foundation failures.

Advantages:

- Increase in the design global factor of safety, and height of the embankment
- Reduction or elimination of stabilizing side berms, thus reducing fill requirements
- Reduction in differential settlement
- Most general contractors can construct GREs and specialty contractors are not required

General Description:

GREs utilize horizontal layers of high-strength geosynthetics to provide reinforcement under or near the base of embankments constructed on soft foundation soils. The geosynthetic can be a geotextile, geogrid, or a combination; the embankment is typically a granular material, although all soil types have been used. The reinforcement is used to increase stability and resistance to deep, rotational embankment foundation failures. The reinforcement does not reduce vertical settlement of the embankment, unless the reinforcement reduces the total volume of fill by permitting steeper side slopes. The reinforcement may help reduce differential vertical settlements. The reinforcement will likely reduce lateral displacement of the foundation soils.

Geologic Applicability:

- Soft foundation soils, with no limitation on the depth of soft soils.
- Potential failure modes vary between shallow and deep, depending on the soft soil depth relative to embankment width.

Construction Methods:

In geosynthetic reinforced embankment applications, a geosynthetic is typically placed on the ground surface or near the bottom of the embankment prior to placing the fill material. The geosynthetic can be a geotextile, geogrid, or a combination of a geotextile and a geogrid. A granular material is typically placed above the geosynthetic in specific patterns using lightweight construction equipment.

Additional Information:

Cost savings versus excavation and replacement, staged construction of fill, and preloading with prefabricated vertical drains are realized by eliminating or significantly reducing the number and/or duration of construction stages, and possibly through the use of steeper fill slopes to reduce the amount of embankment fill required to achieve planned grades. Thus, an embankment can be opened to construction traffic much sooner. Cost savings versus conventional unreinforced embankment can also be realized by reduced right-of-way requirements and less embankment fill material.

SHRP2 Applications:

- New embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- Westwego to Harvey Canal Levee, Louisiana

Complementary Technologies:

Prefabricated vertical drains and fill preloading under appropriate project and subsurface conditions to reduce time to be able to use the embankment. Sand compaction piles in lieu of PVDs. Lightweight fills can also be used.

Alternate Technologies:

Excavation and replacement, prefabricated vertical drains and fill preloading, vacuum preloading with and without PVDs, deep dynamic compaction, vibrocompaction, lightweight fills, and column supported embankments.

Potential Disadvantages:

The total settlement magnitude will likely not be reduced. Detailed field observations are required during construction to monitor pore pressures and to maintain adequate safety factors. This technology is often combined with other special construction measures. When used alone, this technology is not appropriate for projects that cannot accommodate the time necessary for consolidation or for projects where total settlements must be reduced.

Key References for this Fact Sheet:

Holtz, R.D., Christopher, B.R. and Berg, R.R. (2008). Geosynthetic Design and Construction Guidelines, U.S. Department of Transportation, Federal Highway Administration, National Highway Institute, Washington, D.C., FHWA-NHI-07-092.

Rowe, R.K. and Li, A.L. (2005). “Geosynthetic-reinforced embankments over soft foundations.” Geosynthetics International, Special Issue on the Giroud Lectures, 12, No. 1, 50-85.

Bonaparte, R. and Christopher, B.R. (1987). “Design and construction of reinforced embankments over weak foundations,” Reinforced Layered Systems, Transportation Research Record 1153, Transportation Research Board, Washington, DC, 1987, 26-39.

Technology Fact Sheet

COLUMN-SUPPORTED EMBANKMENTS

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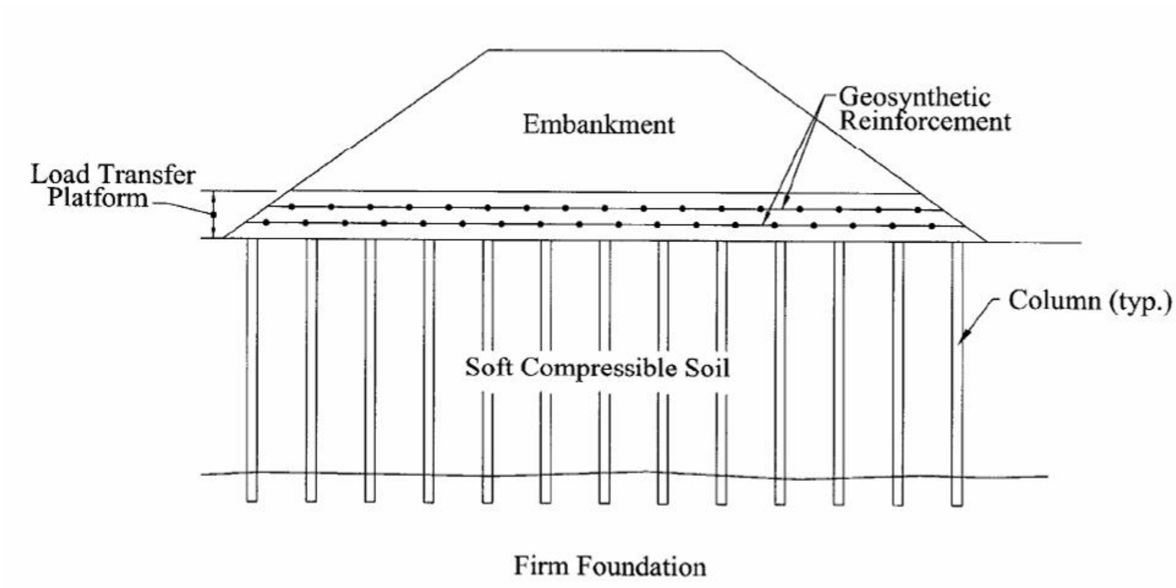

Column Supported Embankment with Geosynthetic Reinforcement
(Figure from Elias et al. (2006))

Basic Function

Column-Supported Embankments (CSE) enable construction of embankments over unstable soils by transferring the load to a stiffer underlying stratum.

Advantages:

- Accelerates construction compared to conventional methods
- Reduces total and differential settlement
- Protects adjacent facilities from distress
- Can be used with a wide variety of columns to accommodate different site conditions

General Description:

Column-supported embankments are used when the soil is too soft or compressible to support the embankment. The columns transfer the load to a firm stratum below the soft layer. The columns can be floating or end-bearing depending on the site geology, the project requirements, and the type of column used. For most CSE applications, the columns are end-bearing. When high-capacity columns with wide spacings are used, geosynthetic reinforcement is typically used at the interface between the top of the columns and the embankment to more efficiently transfer the embankment load to the columns.

Geologic Applicability:

- Typically used on soft compressible clay, peats, and organic soils where settlement and global stability are concerns
- Most cost effective when the compressible material thickness ranges from 15 to 70 feet (4.6 to 21.3 meters)
- Soft soil underlain by stiffer soil or bedrock

Construction Methods:

Columns of strong material are placed in the soft ground to provide the necessary support by transferring the embankment load to a firm stratum. There are numerous types of columns that may be used for this technology (e.g., aggregate columns, vibro-concrete columns, deep mixing method columns, continuous flight auger piles, driven piles with or without pile caps). A load transfer platform or bridging layer may be constructed immediately above the columns to help transfer the load from the embankment to the columns, and thereby permit larger spacing between columns than would be possible otherwise. Load transfer platforms generally consist of compacted soil and geosynthetic reinforcement. The important details of soil type and geosynthetic reinforcement used in the load transfer platform depend on the design procedure employed. Load transfer platforms are used more often when the spacing between columns is relatively large (i.e., greater than 5 feet), which requires higher load carrying capacity from the columns (e.g., vibro-concrete columns, continuous flight auger piles).

Additional Information:

Load transfer platforms are also used to minimize differential settlement when the embankment height is low. Aggregate columns, because of their lower vertical load capacity, are often spaced close enough together that a load transfer platform is not required.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- Rancocas Creek Railroad Bridge – NJ
- I-95/Route 1 Interchange – Alexandria, VA
- Minnesota TH241 Widening – St. Michael, MN

Complementary Technologies:

Many different column technologies can be used with CSEs. Some applications may use lightweight fill in combination with column supported embankments.

Alternate Technologies:

Technologies for similar applications include preloading with or without PVDs, lightweight fill, excavation and replacement, staged construction, and geosynthetic reinforcement embankments.

Potential Disadvantages:

CSEs can incur a higher cost than technologies that require more time before the embankment can be put into service. CSEs suffer form a lack of standard design procedures and lack of knowledge about technology benefits, design procedures, and construction techniques.

Key References for this Fact Sheet:

Collin, J.G. (2007). "U.S. state-of-practice for the design of geosynthetic reinforced load transfer platforms in column supported embankments." GeoDenver 2007, GSP-172: Soil Improvement, CD-ROM.

Filz, G. M. and Smith, M. E. (2007). "Net vertical loads on geosynthetic reinforcement in column-supported embankments." GeoDenver 2007, GSP-172: Soil Improvement, CD-ROM.

Elias, V., Welsh, J., Warren, J., Lukas, R., Collin, J. G., and Berg, R. R. (2006). "Ground Improvement Methods"-Volume I. Federal Highway Administration Publication No. NHI-06-020.

Technology Fact Sheet

LIGHTWEIGHT FILL

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EPS Geofoam Blocks Being Placed
(Phtograph from Elias et al.(2006))

Basic Function

Lightweight fill can be used to reduce settlement and increase stability. It can also be used to reduce the static and seismic horizontal forces applied to earth retaining structures.

Advantages:

- Accelerated construction
- Reduced structural requirements for resisting lateral loads
- Reduced settlement and stability problems
- Suitability for wide variety of projects

General Description:

Lightweight fills have a lower unit weight than regular fills and have been used for roadway embankment construction and for other applications in combination with other technologies to reduce the magnitude of the applied loads. Lightweight fills include geofoam; cellular concrete; wood fiber; shredded tires; Expanded Shale, Clay, and Slate (ESCS); fly ash; boiler slag; and air cooled slag.

Geologic Applicability:

- No geologic or geometric limitations
- Some types of fills should not be used below the ground water table.

Construction Methods:

Many types of lightweight fills have been used for roadway embankment construction. Geofoam can be placed in blocks. Wood fibers and ESCS are placed in layers and can be compacted if necessary. Certain foams and slurries are blended and placed using forms.

Additional Information:

Lightweight fills with lower unit weights are generally more expensive. Availability affects selection and economics of the different lightweight fills. Using lightweight fill can require less labor for placement than conventional fills.

SHRP2 Applications:

- Embankment and roadway construction over unstable soils
- Roadway and embankment widening

Example Successful Applications:

- New York State Route 23A – New York
- Roadway Lane Addition Southeast – Michigan
- Maine Turnpike Beech Ridge Road Overpass - Maine

Complementary Technologies:

Can be used by itself or can be used with MSE walls, cantilever pile walls, geosynthetic reinforced embankments, and reinforced soil slopes.

Alternate Technologies:

Competes with many other ground improvement technologies including excavation and replacement, reinforcement technologies, and load transfer methods.

Potential Disadvantages:

- Increased material cost
- Environmental concerns
- Long-term performance
- Need to encapsulate some types of fills
- Some types of fill are only locally or regionally available
- Availability of fill influences cost

Key References for this Fact Sheet:

Elias, V., Welsh, J., Warren, J., Lukas, R., Collin, J. G., and Berg, R. R. (2006). Ground Improvement Methods - Volume I, Federal Highway Administration, NHI-06-019.

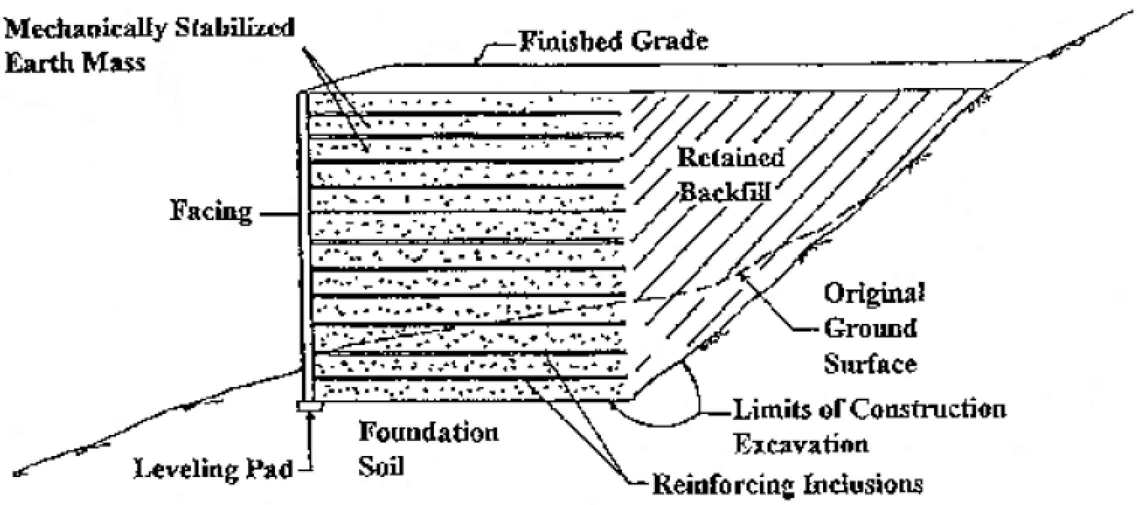
Stark, T.D., Arellano, D., Horvath, J.S., and Leshchinsky, D. (2004a). "Guideline and recommended standard for geofoam applications in highway embankments". NCHRP Report 529 (Project 24-11), National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C.

Stark, T.D., Arellano, D., Horvath, J.S., and Leshchinsky, D. (2004b). "Geofoam applications in the design and construction of highway embankments". NCHRP Web Document 65 (Project 24-11).

Technology Fact Sheet

MECHANICALLY STABILIZED EARTH WALLS

November 2012 http://www.GeoTechTools.org



Mechanically Stabilized Earth Mass - Principal Elements

(Figure from Berg et al. (2009))

Basic Function

Mechanically Stabilized Earth Wall Systems (MSE walls) use reinforced soil to create a composite retaining wall system which can be used where change in grade is necessary.

Advantages:

- Simple and rapid construction procedures
- Reduced right of way
- Cost effective compared to traditional walls
- Aesthetically pleasing appearance

General Description:

Reinforced soil consists of tensile reinforcements added to soil to form a stronger composite material mass. The general acceptance, expiration of patents, and widespread use of this type of construction has led to generically naming retaining wall construction as Mechanically Stabilized Earth Walls (MSEW). Reinforced soil structures are generally classified as a wall when the face batter is equal to or greater than 70 degrees from horizontal, and are classified as Reinforced Soil Slopes (RSS) when the face batter is shallower. MSE walls are cost effective compared to conventional concrete cantilever retaining wall systems, especially for walls in fill embankment cross sections, and should be considered when selecting a retaining wall type. Furthermore, MSE walls are more flexible than conventional retaining walls and, therefore, are suitable for sites with poor foundations and seismically active areas. Recent related developments in reinforced soil applications such as modular block/geosynthetics walls and Tecco mesh/shotcrete facing systems are included with the MSEW technology.

Geologic Applicability:

- Particularly suited to economical construction in fill embankments, steep-sided terrain, in ground subject to slope instability or in areas where foundation soils are poor.
- Cost-effective alternatives for most applications where reinforced concrete or gravity type walls have traditionally been used to retain soil.
- Bridges may be supported directly on top of the MSEW

(via a spread footing) or on deep foundation elements that pass through the reinforced soil mass.

- Also used for temporary structures, which is especially cost-effective and time-efficient for temporary detours necessary for highway reconstruction projects.

Construction Methods:

Construction is well established, using placement of reinforcement followed with compaction of the fill over the reinforcement.

Additional Information:

A variety of facings for MSE walls are currently available and in use. Common facings include: precast concrete panels, dry cast modular blocks, gabions, L-shaped welded wire mesh, shotcrete, wood lagging and panels and wrapped sheets of geosynthetics. Currently, most process patents covering soil-reinforced system construction or components have expired, leading to a proliferation of available systems.

SHRP2 Applications:

- Roadway and embankment widening
- Stabilization of pavement working platforms

Example Successful Applications:

- 12.6 m High Geotextile-reinforced Wall, Seattle, WA
- Crosstown Project, Minneapolis, MN
- Veterans Memorial Overpass, Tucson, AZ

Complementary Technologies:

Reinforced soil slopes, Shored MSE wall systems, lightweight fills, column supported embankments.

Alternate Technologies:

Traditional concrete cantilever retaining wall structures and reinforced soil slopes.

Potential Disadvantages:

- Corrosive nature of fill material on reinforcements
- May require large space behind wall to obtain sufficient internal and external stability
- Wide variety of facings available and selection of appropriate facing not well defined
- Clay and silt soils have poor drainage and are poor fill materials.
- Durability of some reinforcements may reduce service life

Key References for this Fact Sheet:

AASHTO (2010). LRFD Bridge Design Specifications. 5th Edition, American Association of State Highway and Transportation Officials, Washington, D.C.

Berg, R.R., Christopher, B.R. and Samtani, N.C. (2009). Design and Construction of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, FHWA NHI-10-024 Vol I and NHI-10-025 Vol II.

Tanyu, B.F, Sabatini, P.J and Berg, R.R (2008). Earth Retaining Structures Reference Manual. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., FHWA NHI-07-071, 654 p.

Sullivan, J. (1996). Pavement Recycling, Executive Summary and Report. FHWA-SA- 95-060.