1.0 Ground Modification

Ground modification technologies are geotechnical construction methods used to improve poor ground conditions when removal and replacement, avoidance of such conditions, or the use of deep foundations is infeasible or too costly. Ground modification may be used to:

- Mitigate liquefiable soils.
- Improve loose or soft soil to reduce settlement, increase bearing capacity, shear, or frictional strength as well as overall improvement of stability for embankment and structure foundation.
- Improve slope stability for mitigation of landslides.
- Increase density.
- Decrease imposed load.
- Form seepage cutoff or fill voids.
- Accelerate consolidation.
- Control deformation.
- Provide/increase lateral stability.
- Reduce earth pressures.

There are three strategies available to accomplish the above functions:

1. Increase shear strength, density, and/or decrease compressibility of foundation soil,
2. Reduce the applied load on the foundation soil by the use of lightweight fills,
3. Transfer the load to a more competent (deeper) foundation soil.

Ground Modification Methods, Volumes I and II, FHWA NHI-16-027 and FHWA NHI-16-028, April2017 are frequently referenced in this module. The Geoprofessional should consult each volume for details concerning a specific ground modification method. Also be aware of new and innovative ground modification methods. If a new or innovative ground modification method is to be considered on a Caltrans project, the method should be discussed with the Project Development Team including Construction. Sometimes it will become necessary to initiate a construction evaluation project to measure the effectiveness of a new or innovative ground modification technique prior to its use.

A web-based information and guidance system, *Geotechnical Solutions for Transportation Infrastructure* (*Geotech Tools*), presents information on geoconstruction technologies and provides a tool to assist in deciding which technologies are potentially applicable to site-specific conditions. The following ground modification techniques are addressed in *Geotech Tools*:

- Aggregate columns/Stone Columns/Rammed Aggregate Piers
- Beneficial Reuse of Waste Materials

- Bio-Treatment for Soil Stabilization
- Blast Densification
- Bulk-Infill Grouting
- Chemical Grouting/Injection Systems
- Chemical Stabilization of Subgrades and Bases
- Column Supported Embankments
- Combined Soil Stabilization with Vertical Columns (CSV)
- Compaction Grouting
- Continuous Flight Auger Piles
- Deep Dynamic Compaction
- Deep Mixing Methods
- Drilled/Grouted and Hollow Bar Soil Nailing
- Electro-Osmosis
- Excavation and Replacement
- Fiber Reinforcement of Slopes
- Geocell Confinement in Pavement Systems
- Geosynthetic Reinforced Construction Platforms
- Geosynthetic Reinforced Embankment
- Geosynthetic Reinforcement in Pavement Systems
- Geosynthetic Separation in Pavement Systems
- Geosynthetics in Pavement Drainage
- Geotextile Encased Columns
- High-Energy Impact Rollers
- Helical Soil Nails
- Hydraulic Fill with Geocomposite and Vacuum Consolidation
- Injected Lightweight Foam Fill
- Intelligent Compaction
- Jet Grouting
- Lightweight Fill, EPS Geofoam, Low Density Cementitious Fill
- Mass Mixing Methods
- Mechanical Stabilization of Subgrades and Bases
- Mechanically Stabilized Earth Wall System
- Micropiles
- Onsite Use of Recycled Pavement Materials
- Partial Encapsulation
- Prefabricated Vertical Drains and Fill Preloading

- Rapid Impact Compaction
- Reinforced Soil Slopes
- Sand Compaction Piles
- Soil Nail Wall
- Shoot-In Soil Nailing
- Shored Mechanically Stabilized Earth Wall System
- Traditional Compaction
- Vacuum Preloading with and without PVDs
- Vibro-Concrete Columns
- Vibrocompaction

2.0 Selection Process

Selection of an appropriate ground modification technology requires consideration of technologies and site-specific project goals and challenges. Use the steps in Table 1 to select the appropriate method.

Table 1: Selection Process (after Ground Modification Methods)

Step	Process
1	Identify potential poor ground conditions, including extent and type of negative impact
2	Assess remove and replace and avoidance options – if infeasible or too expensive consider ground modification
3	Identify or establish performance requirements
4	Identify and assess any space or environmental constraints
5	Determine subsurface conditions – Type, depth, and extent of poor soil as well as groundwater table depth and assessment of shear strength and compressibility
6	Make preliminary selection – consider performance criteria, limitations imposed by subsurface conditions, schedule and environmental constraints, and the amount of improvement required (Table 2 should be used in this selection process)
7	Perform preliminary design
8	Compare and select – selection is based on performance, constructability, cost, and any other relevant project factors

Ground modification categories, functions, methods, and applications are summarized in Table 2.

Table 2: Ground Modification Categories, Functions, Methods and Applications (after Ground Modification Methods)

Category	Function	Method	Application
Consolidation	Accelerate consolidation and increase shear strength	1- Prefabricated vertical drains 2- Surcharge	Viable for normally consolidated clays. Can achieve up to 90% consolidation in a few months
Load Reduction	Reduce load on foundation and reduce settlement	1- Geofoam (EPS) 2- Foamed (Cellular) Concrete 3- Lightweight fill	Density varies from 6-76 lb/ft3. Granular fills usage subject to local availability.
Densification	Increase density, bearing capacity, and friction strength of granular soils. Decrease settlement and increase resistance to liquefaction	1- Vibro-Compaction 2- Dynamic Compaction by falling weight impact	Vibrocompaction viable for clean sands with up to 15% fines. Dynamic compaction limited to depth of about 33 feet, but is applicable for a wider range of soils. Both methods can densify granular soils up to 80% Relative Density. Dynamic Compaction generates vibrations for a considerable lateral distance.
Reinforcement	In soft foundation soils, increases shear strength, resistance to liquefaction, and decreases compressibility. Internally reinforces fills and/or cuts.	1- Stone Column 2- Rammed Aggregate Piers 3- MSE retaining walls 4- Soil Nail walls	Soil Nailing may not be applicable in soft clays or loose fills. Stone columns applicable in soft clay profiles to increase global shear strength and reduce settlement.
Chemical Stabilization by Deep Soil Mixing	Physio-chemical alteration of foundation soils to increase their tensile, compressive, and shear strength; to decrease settlement; and/or provide lateral stability and/or confinement	1- Wet mixing methods using primarily cement 2- Dry mixing methods using lime-cement	Applicable to soft to medium stiff clays for excavation support where the groundwater table must be maintained or for foundation support where lateral restraint must be provided or to increase global stability and decrease settlement. Required significant QA/QC program for verification.

Category	Function	Method	Application
Chemical Stabilization by Grouting	To form fill voids, increase density, increase tensile, and compressive strength	1- Permeation Grouting with particulate chemical grouts 2- Compaction Grouting 3- Jet Grouting 4- Bulk filling 3- Injected Lightweight Foam Fill	1) Permeation grouting to increase shear strength or for seepage control. 2) Compaction grouting for densification and 3) Jet grouting to increase tensile and/or compressive strength of the foundations, and 4) Bulk filling of any subsurface voids. 5) Inject lightweight foam to fill voids and lift pavements and slabs w/o adding weight.
Load Transfer	Transfer load to deeper bearing layers	5- Column Supported Embankment (CSE) on flexible geosynthetic mats	Applicable for deep soft soil profile or where a tight schedule must be maintained. A variety of stiff or semi-stiff piles can be used.

Geotech Tools contains a technology selection assistance tool that provides solution options. The following information is available for each method:

- Technology Fact Sheets
- Photographs
- Case Histories
- Design Guidance
- Quality Control/Quality Assurance
- Cost Information
- Specification Guidance
- Bibliography

3.0 Design Parameters for Ground Modification Analyses

Specific geotechnical data that will need to be developed during the investigation depends upon the ground modification technique chosen. Ground Modification Methods should be referred to for specific geotechnical data needed for various types of ground modification techniques.

4.0 Design Requirements

The following documents should be used for design:

- *Ground Modification Methods*, Reference Manual Volume I and II, FHWA NHI-16-027 and FHWA NHI-16-028, April 2017
- *Geotech Tools, Geo-Construction Information and Technology Selection Guidance for Geotechnical, Structural, and Pavement Engineers*, SHRP2, Transportation Research Board
- *Design and Construction of Stone Columns – Vol. I*, Federal Highway Administration, FHWA/RD-83/026, Barksdale, R. D., and Bachus, R. C., 1983.
- *Geotechnical Engineering Circular No. 1 – Dynamic Compaction*, Federal Highway Administration, FHWA-SA-95-037, Lukas, R. G., 1995.
- *Guideline and Recommended Standard for Geofoam Applications in Highway Embankments*, NCHRP Report 529, Transportation Research Board, 2004.
- *Guideline and Recommended Standard for Geofoam Applications in Highway Embankments*, NCHRP Report 529, Transportation Research Board, 2004.
- *Prefabricated Vertical Drains – Vol. I: Engineering Guidelines*, Federal Highway Administration, FHWA/RD-86/168, Rixner, J. J., Kraemer, S. R., and Smith, A. D., 1986.

5.0 Ground Modification Methods used by Caltrans

Caltrans has used the following ground modification methods (see Appendix 1):

- Prefabricated Vertical Drains (PVDs) and Fill Preloading
- Lightweight Fills (natural volcanic, cellular concrete, Expanded Polystyrene (EPS), Expanded Shale, Shredded Tires, and Saw Dust)
- Geosynthetic Reinforced Embankments
- MSE Walls and Reinforced Soil Slopes
- Soil Nailing
- Stone Columns/Rammed Aggregate Piers
- Compaction Grouting
- Injected Lightweight Foam Fill
- Permeation Grouting
- Deep Soil Mixing
- Micropiles

Sections 5.1 through 5.3 provide details (Introduction, Investigation, Design Methods, Reporting, and Considerations for Construction) on three ground modification techniques commonly used by Caltrans: Prefabricated Vertical Drains, Lightweight Fill (Expanded Polystyrene and Cellular Concrete) and Stone Columns/Rammed Aggregate Columns.

5.1 Prefabricated Vertical Drains (PVD) and Surcharge

Prefabricated Vertical Drains (PVD) (formally “wick drains”) are band shaped (rectangular cross-section) geocomposite products consisting of a geotextile filter material surrounding a plastic drainage core. PVD are used to accelerate the settlement and shear strength gain of saturated, soft foundation soils by shortening the drainage path length. PVD are commonly coupled with surcharge fills to facilitate accelerated embankment construction with minimal post-construction settlement.

Advantages of PVD with surcharge are:

- Decreased construction time
- Low cost versus other ground modification technologies
- No spoil
- High production rate
- Durable
- Relatively straightforward and simple QC/QA procedures

Projects that have used PVD are:

- ALA-80 SFOBB Oakland Touchdown (OTD) Geofill (EA 04-01205)
- SOL-37 Widening project (EA 04-0T141)
- ALA-880- 5th Avenue Bridge Seismic Bridge Replacement (EA 04-1706U)
- SJ-4 Widening (EA 10-0H04U)
- MEN-101 Willits Bypass (EA 01-26200)
- SJ-12 Bouldin Island (EA 10-0G800)
- SD- 5 (EA 11-0301U)

Installation of PVD requires site preparation, construction of a drainage blanket and/or a working mat, and installation of the PVD. Site preparation includes removal of vegetation and surface debris, and obstacles that would impede installation of the PVD. It may be necessary to construct a working mat to support construction equipment, which can later serve as the drainage blanket. There are many different ways of installing PVD, 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.

Design considerations include drain spacing (typically triangular from 3 to 8 feet spacing with 3 to 6 ft common), flow resistance, and installation disturbance. Quality control tests usually relate to the material properties of the drain and the measurement of settlement and dissipation of excess pore water pressures during consolidation.

5.1.1 Investigation

The investigation for PVD is similar to the investigation for embankment stability and settlement (see *Embankment* module). PVD do not require any special considerations during the field investigation.

5.1.2 Design Methods

The Federal Highway Administration (FHWA) has design documents for both of the preferred design procedures for this technology:

- Prefabricated Vertical Drains, FHWA-RD-86-168, 1986
- Ground Modification Methods, Volume 1, FHWA-NHI-16-027, April 2017

Design parameters include the selection of the drain type, drain spacing, drain length, and the amount of preload needed to achieve a specified consolidation within an allotted time.

The design begins with traditional settlement analyses without PVD to determine the total magnitude and time rate of settlement under final project loads. Then the use of PVD is analyzed to reduce the time to reach the final consolidation settlement.

The first step of the design process is to establish project time requirements, anticipated service loads, and the acceptable amounts of post-construction settlement. A subsurface investigation and laboratory soil-testing program are then performed to provide information about the soil stratigraphy and engineering properties of the compressible soil. Based on this information, the amount of total settlement due to primary consolidation and secondary consolidation can be estimated as well as the time for this settlement to occur. If the time to reach 90 to 95 percent of the total project settlement is too long, PVDs should be considered to reduce the time required for consolidation settlement.

PVD spacing should be determined using the Barron-Hansbo relationship that relates the time to achieve a desired average degree of consolidation to drain diameter, drain spacing, and coefficient of consolidation.

An example calculation of staged fill construction is provided in the Washington Department of Transportation (WASHDOT) Geotechnical Design Manual, Appendix 9A.

5.1.3 Reporting

The GDR should include sections that:

- Justify the use of PVD with surcharge fill if required. State predicted settlement and time to achieve both with and without PVD. Discuss foundation bearing capacity failure or slope instability during staged construction and associated staging requirements. (See *Embankment* module)
- Justify the selection of PVD as the preferred treatment strategy, including such considerations as constructability, cost, and overall project specific effectiveness.

- Provide layout and cross sections of ground modification area showing limits, PVD pattern, and depths of PVDs, stability berm height and location (if used), loading rates, and settlement period.

5.1.4 Field Instrumentation and Considerations for Construction Including QA/QC

Considerations typically include:

- Requirements for field splicing and connecting PVD to drainage pipes and/or drainage blankets/working platforms as required;
- Site accessibility issues for heavy equipment including working platform or ground pressure limitations for very soft surficial ground conditions;
- Difficult PVD installation due to presence of obstructions which may require pre-auguring;
- Confirming that PVD are installed to correct depth in field by appropriate field observations (both to ensure not too short or too long);
- Coordination with District Environmental on any site-specific requirements for pore water discharge (if applicable); and
- A comprehensive geotechnical instrumentation program to confirm settlements and/or stability of embankment is achieved (whether by CT personnel or contractor provided) with clearly defined scope and reporting requirements and sufficient redundancy to handle potential for equipment malfunction/damage and adequately cover planned construction staging.

A key consideration of the geotechnical instrumentation program is to layout the required type, location and depth of monitoring taking into account the proposed construction staging with sufficient redundancy of monitoring points. This is particularly needed for contractor supplied, installed, and monitored instrumentation as less control over data quality is exercised. If the project has stability concerns and controlled loading rates, more detailed and comprehensive instrumentation may be required.

5.1.5 Specifications

Refer to *Geotech Tools* to create a project-specific NSSP.

5.2 Lightweight Fills

Lightweight fill materials are used to reduce the magnitude of the applied loads to:

- Eliminate or significantly reduce embankment settlement.
- Reduce active pressure behind retaining walls and abutments.
- Reduce driving force in landslide repair.
- Increase an embankment’s resistance to seismic loads.

Lightweight fills have primarily been used at Caltrans for reducing embankment settlement at bridge approaches and to reduce the driving force of landslides.

In cases where a soft soil deposit is very thick, partial excavation of the native material directly below the embankment (and backfill with lightweight material) will help to balance the total imposed load. The amount of excavation depends on the unit weight of the material to be excavated and the unit weight of the lightweight fill to be used. The lighter the material the less excavation would be required. Sometimes it is not possible to use lightweight fill to completely offset an additional embankment load, however, it can reduce the additional load to a tolerable amount.

Common lightweight fill materials used by Caltrans are:

- Expanded Polystyrene (EPS) or Geofoam
- Cellular Concrete (Foamed Concrete)
- Natural (volcanic) lightweight materials

Expanded shale, wood fiber (saw dust), and shredded tires have been used by Caltrans. Expanded shale is seldom used in Caltrans for embankment construction due to its relatively high cost. Wood fiber (saw dust) is seldom used in Caltrans for embankment construction due to its lack of availability in large quantity. Shredded tires have been used in three Caltrans projects and its use is encouraged by the California Department of Resources Recycling and Recovery in their effort to reduce stockpiles of disposed tires. FHWA issued an Interim Guideline to limiting the maximum layer thickness for shredded tire fills to 10 feet.

Consider the following when selecting a lightweight fill:

- Availability of lightweight fill materials;
- The engineering properties of the lightweight fill material for use in both settlement and slope stability analysis. For example, for granular lightweight fill, the geoprofessional must evaluate the density, the angle of shearing resistance or cohesion of the lightweight fill. Whereas, for EPS and cellular concrete, in addition to the density, compressive strength must be evaluated;
- The durability, water absorption potential, corrosion potential, and other unique characteristics;
- Costs for using lightweight fill versus conventional construction.

Table 3 provides a list of various lightweight materials with the range of densities, and specific gravities:

Table 3: Lightweight Fill Materials

Lightweight Fill Type	Range of Density (pcf)	Range of Specific Gravity
Natural (Volcanic) Material	50 to 75	0.80 to 1.2
Expanded Polystyrene (EPS)	0.8 to 2	0.01 to 0.03
Cellular (Foamed) Concrete	20 to 61	0.3 to 0.8
Wood Fiber (Saw Dust)	34 to 60	0.6 to 1.0
Shredded Tires	37 to 56	0.6 to 0.9
Expanded Shale	37 to 65	0.6 to 1.0
Fly Ash	70 to 90	1.1 to 1.4
Boiler Slag	62 to 109	1.0 to 1.8
Air-Cooled Slag	69 to 94	1.1 to 1.5

For more information regarding design parameters (density, angle of shear resistance, permeability and compressibility), environmental considerations, design and construction of granular lightweight fill such as Wood Fiber, Air- Cooled blast Furnace, Fly Ash, Boiler Slag, Expanded Shale and Shredded Tires refer to August 2006 FHWA NHI-06-019, Tables 2 through 7.

5.2.1 Expanded Polystyrene (EPS)

The most comprehensive design, material, and construction guidelines on the use of Expanded Polystyrene (EPS) for highway construction have been summarized in NCHRP 24-11 for embankments and 24-11(02) for slope stability projects. Additional design information is summarized by Horvath (1995).

5.2.2 Cellular Concrete (Foamed Concrete)

Cellular concrete consists of cement, water, a foaming agent, and optional admixtures. Cellular concrete is self leveling and can be pumped up to 3300 feet, and will begin to harden between 2 to 6 hours after production. Cellular concrete can be pumped at 100 cubic yards per hour. The density of cellular concrete typically ranges from 25 pcf to as high as 65 pcf. Relative to soil the shear strength is much higher. If significant differential settlement is anticipated the designer should be aware that cellular concrete (due to its relatively brittle nature) could crack, losing much of its shear strength. The unit cost of cellular concrete can be high especially for small quantities.

Caltrans has used cellular concrete in several large and small projects to reduce embankment settlement, to reduce landslide driving forces, and to reduce active pressures behind retaining walls. Cellular concrete has also been used as backfill for tunnel, waterlines and sewers, to provide shock absorption in earthquake zones, and to fill voids in silos and abandoned mines.

The advantages of using cellular concrete compared to other types of lightweight materials are:

- Easily placed by pump or gravity for rapid installation
- Broad range of densities and compressive strengths
- Durable and noncorrosive
- High slump and self leveling
- Absorbs shock waves
- High freeze-thaw resistance
- Low water absorption and permeability
- No compaction is required
- Cost is comparable or even less than most granular lightweight materials

The disadvantages of using cellular concrete compared to other types of lightweight materials are:

- The cost of cellular concrete increases with cast density.
- The cost is relatively high for small jobs.
- Requires qualified cellular concrete contractors and their suppliers.

5.2.3 Investigations (EPS and Cellular Concrete)

The field exploration and laboratory testing should include:

- Determining the thickness of soft foundation soil by drilling or by CPT sounding.
- Performing in situ strength testing using Cone Penetration Test (CPT) or Vane Shear Test (VST).
- Determining the groundwater level (monitoring may be required).
- Obtaining undisturbed soil samples for laboratory testing using the modified California sampler, Shelby tubes, and pitcher barrel.
- Performing laboratory tests on samples of soft foundation soil to determine particle gradation, moisture contents, unit weight, void ratio, shear strength (Su) unconfined compressive strength (q_u), coefficient of consolidation (Cv), and permeability.
- Use of geophysical testing methods maybe considered for determining thickness of soft layers. PS Suspension logging maybe used for determination of in situ strength.

5.2.4 Design Method (EPS)

EPS is approximately 1/100th the weight of conventional fills and therefore is highly effective at reducing driving forces or settlement potential. EPS dissolves in gasoline and other organic fluids or vapors and therefore must be encapsulated in a gasoline resistant geomembrane where such organics could potentially reach the EPS. Other design considerations for EPS include creep, flammability, buoyancy, moisture absorption, photo-degradation, and differential icing of pavement constructed over EPS.

The EPS design process includes:

- Design for external (global) stability. This includes consideration for settlement, bearing capacity, and slope stability under the projected loading conditions.
- Design for internal stability within embankment mass. The designer must insure the EPS geofoam can support the overlaying pavement and traffic loads without immediate and time dependent creep compression.
- Design of the appropriate pavement system over the EPS.
- Design to protect the EPS to resist hazards like fire and gasoline leakage- This can be done by using gasoline resistant geomembrane.
- Design for uplift pressure. This is necessary if high groundwater exists and if the 100-year flood level creates high head in surrounding areas. In some cases where uplift is an issue, the use of a cutoff wall may be necessary.
- The foundation under the EPS must be prepared to create a smooth surface and dry condition. In cases where groundwater exists, dewatering may become necessary.

External stability analyses generally follow traditional geotechnical procedures, although stress distribution must consider a non-homogenous embankment. For shear strength, NCHRP- 24-11 recommends using only ¼ of EPS geofoam compressive strength.

Internal stability analyses are based on the properties of the EPS type selected to support the imposed loads from overlying pavement and traffic. The design approach for internal stability is a deformation-based methodology using the total stress from all loads on EPS blocks, elastic limit stress, and the initial tangent modulus to evaluate load-induced deformations. Refer to FHWA-NHI-16-027, Table 3-2 for the minimum recommended values of elastic limit stress for various EPS densities.

NCHRP- 24-11 provides detailed design methods, examples, typical construction details, and design charts for external, internal, and pavement design. FHWA-NHI-16-027, Table 3-3 summarizes the range of design parameters and design considerations associated with the use of EPS.

Regarding environmental considerations, Table 3-3 of FHWA-NHI-16-027 states that there are no known environmental concerns regarding EPS and no decay of the material occurs when placed in the ground.

5.2.5 Design Method (Cellular Concrete)

The design of cellular concrete must balance the need for load reduction with compressive strength requirements. Due to high air content in cellular concrete, it generally has much lower strength than conventional concrete. Applications that require high compressive strength, such as foundations, should use higher density cellular concrete. For many applications, such as flowable fill in trench lines or behind retaining walls, the compressive strength can be as low as 100 psi. For use as lightweight fill in embankment construction, a compressive strength ranging from 80 to 200 psi would be sufficient.

The design process for cellular concrete in embankments should include:

- Design for external (global) stability. This includes consideration for settlement, bearing capacity, and slope stability under the projected loading conditions.
- Design for internal stability within embankment mass. The designer must insure the cellular concrete can support the overlaying pavement and traffic loads without cracking and creep compression.
- Design of the appropriate pavement system over cellular concrete. Communicate with District Materials regarding the most appropriate pavement design.
- The lower compressive strength mixes are affected by freeze-thaw cycles. The product should be used below the zone of freezing or a higher compressive strength used. Densities greater than 37 pcf have reported excellent freeze-thaw resistance.
- Design for uplift pressure. Necessary if high groundwater exists and if the 100-year flood level creates a peizometric head in surrounding areas. In some cases where uplift is an issue, the use of a cutoff wall may be necessary.
- The foundation under the cellular concrete must be prepared and compacted to create a smooth surface and dry condition. In cases where groundwater exists, dewatering may become necessary. In addition, a layer of permeable material (8 to 12 inches) wrapped in filter fabric including a layer of geomembrane on top directly below cellular concrete may become necessary when excess groundwater is present.

Table 3-4 of FHWA-NHI-16-027 states that there are no known environmental concerns regarding cellular concrete.

5.2.6 Reporting (EPS and Cellular Concrete)

The GDR should include sections that:

- Justify the use of a ground modification method, such as excessive predicted settlement, foundation bearing capacity failure, or slope instability.
- Justify the selection of type of lightweight fill to be used, including such considerations as constructability, cost, and effectiveness.
- Provide detailed layout, profile and cross sections of ground modification to be treated with lightweight fill. The profile and cross sections should show limits, depth of excavation to be backfilled with lightweight material, and height of the lightweight fill material and supporting engineering results.
- If lightweight material is to be used as backfill behind retaining walls, justify its use such as reduction in active pressure and elimination of settlement and provide detailed cross sections.

- Provide instrumentation and monitoring plans and specifications (either Caltrans approved SSP and/or NSSP).

5.2.7 Considerations for Construction (EPS)

FHWA-NHI-16-027, Table 3-3 summarizes a list of important considerations such as:

- Subgrade preparations before placement of EPS blocks;
- Placement and interlocking of EPS blocks when multiple layers are used;
- Mechanical connections between EPS blocks;
- Covering of EPS blocks to prevent exposure to sunlight and displacement from wind or buoyancy.

For monitoring and construction control for EPS blocks, field monitoring should include measurements of the density and compressive strength of the materials supplied. For EPS blocks, the density and compressive strength will be a function of the grade delivered with appropriate manufacturer QC documentation. Samples should be obtained for QA testing. Observations of the placements of the blocks should also be made to confirm that the blocks are placed without a continuous joint and that shear transfer plates are installed between successive lifts of the blocks. The gasoline resistant geomembrane covering the blocks should be measured to confirm thickness and complete enclosure of the blocks. The seams within the geomembrane should be sealed properly.

5.2.8 Considerations for Construction (Cellular Concrete)

FHWA-NHI-16-027, Table 3-4 summarizes a list of important considerations such as:

- Required a staging area for batching, mixing, and placing on site;
- Required forming for placement of cellular concrete in stages;
- The lift thickness of each pour should be measured to ensure that it does not exceed the maximum thickness specified in the specifications;
- Adequate time as specified in the specifications should be allowed for cellular concrete to harden sufficiently prior to placement of the next lift. The materials must support foot traffic prior to casting subsequent lifts.
- Samples of the freshly mixed fill should be obtained at the point of placement in a manner similar to concrete testing for performance of density and compressive strength tests.

5.2.9 Specifications (EPS and Cellular concrete)

Non-standard specifications from previous Caltrans projects are available on the Caltrans intranet at the DRS and/or OE advertised projects web page. In addition, typical and sample specifications are available in FHWA NHI-06-027 and Geotech Tools website.

5.3 Stone Columns and Rammed Aggregate Columns

Stone columns and rammed aggregate columns (RAC) use aggregate to create stiff columns to increase bearing capacity, shear strength, rate of consolidation, and liquefaction resistance, and to reduce settlement. Rammed aggregate columns can be designed to provide uplift capacity. Stone columns do not provide uplift capacity. Example applications of these methods include:

- Support for roadway or bridge approach embankments over unstable soils. Examples: SON-101/Airport Blvd I/C project (EA 04-3A23U1) and MRN/SON-101 Marin Sonoma Narrows B-3 project (EA 04-264091),
- Support for structures, such as bridge approaches and retaining walls. Example: SON-101/Airport Blvd I/C project (EA 04-3A23U1, and ALA-92/880 Interchange project (EA 04- 01611)
- Slope stabilization. Example: SF-1 Mt. Lake project (EA 04-1A9021) and ALA-580, Widening project (EA 04- 4A0701),
- Liquefaction mitigation. Example: SF-1 Mt. Lake project (EA 04-44010), Seismic Retrofit project ALA-260 (EA 44010) and SD-5 (EA 11-0301U)

Stone columns are formed with gravel or crushed rock in a pattern to create a composite foundation of the columns and surrounding soil. The stiff columns carry a larger load than the surrounding soil resulting in increased bearing capacity and reduced settlement. Stone columns can be installed by either vibro-replacement (a water jetting, top feed method), or vibro-displacement (an air jetting, top or bottom feed method). However, due to environmental considerations, approval of the vibro-replacement method may be difficult to obtain in California. In both installation 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.

Rammed aggregate columns (RAC) consist of aggregate-filled drilled holes that form stiff, high density piers. However, unlike a stone column a high-energy beveled tamper typically mounted on an excavator is used to compact the aggregate. As the aggregate is rammed to form the columns, the aggregate is forced laterally into the sidewalls of the hole, partially densifying the surrounding soil. To provide uplift capacity, a metal frame anchored between the bottom lifts is included in the pier.

Both methods have the advantages of:

- Rapid installation
- Cost effectiveness compared to other foundations options
- Creating a shortened drainage path to accelerate consolidation
- Allowing for high level of compaction
- Efficient QC/QA procedures

Although both methods have similar ranges of applications, the vertical ramming force applied on RAC can develop much higher bearing capacity in the columns. RAC are more expensive, and may be subject to proprietary constraints.

Table 4 presents factors to consider when selecting either stone columns or rammed aggregate columns.

Table 4: Design Considerations for Stone Columns and Rammed Aggregate Columns

	Stone Columns	**Rammed Aggregate Columns**
Suitable materials for treatment	Clays, silts, and loose silty sands (shear strength c=300 to 2000 psf)	Soft organic clays, stiff to very stiff clays, loose silty sand, medium dense to dense sands, uncompacted fill.
Unsuitable materials for treatment	Peat, organic soil, very soft clay (c<200psf) with layer thickness greater than 1~2 column diameters	Very soft clays (c<300 psf), very loose sands (SPT<1)
Treatment depth	20-30 ft typical, up to 90 ft	7 – 30 ft
Load bearing capacity	40-60 kips typical, 110 kips max.	50-150 kips
Settlement	Reduced by 30-50% of unimproved ground	Reduced to less than 1”
Backfill material	Vibro-replacement: uniform, round to subangular gravel (1 to 2.5 inches) Vibro-displacement: well-graded gravel/cobble (3/8 to 4 inches)	Uniform gravel (2 to 3 inches)

Alternatives to stone columns and rammed aggregate columns include site preloading, excavation and replacement, driven piles, deep-soil-mixing columns, jet grout columns, and drilled shafts.

There are other emerging alternatives to stone columns and rammed aggregate columns, including vibro-concrete columns, geotextile encased columns, gravel drains, sand compaction piles, and rammed stone columns. These alternatives may prove applicable where stone columns / rammed aggregate piers are not. For more details about these alternatives, refer to Ground Modification Methods Manual.

5.3.1 Investigations

Table 5 lists design parameters for stone columns / rammed aggregate columns that should typically be obtained from field exploration. Note that not all listed parameters may be needed for a project.

Table 5- Design Parameters for Stone Columns/Rammed Aggregate Columns

Parameter	Field Exploration Method
Thickness of layer to be treated	Boring (SPT, CPT, soil tube)
$(N1)_{60}$ of untreated and treated soil*	SPT boring
Normalized tip resistance $(q_c)_1$ of untreated and treated soil	CPT boring
Shear Strength (S_u) of untreated and treated soil	• Pocket Penetrometer Test (PP) • Vane Shear Test (VS) • Torvane (TV)
Shear wave velocity (Vs) of untreated and treated soil	• Seismic CPT boring • Correlations with $(N_1)_{60}$ / $(q_c)_1$ / Su • Geophysical methods
Modulus of subgrade reaction (k)	Field plate load test

* Untreated soil: Soil that has not had ground modification treatment; treated soil: soil that has had ground modification, e.g. soil mass before and after stone column installation.

Design parameters and data that should be obtained from laboratory tests for untreated soil are:

- Particle gradation
- Unit weight
- Void ratio
- Shear strength (Su)
- Compressibility
- Coefficient of consolidation
- Permeability

Design parameters that are usually obtained from correlations with other parameters include friction angle, elastic modulus, and Poisson’s ratio (see EPRI, 1990).

5.3.2 Design Methods

Support of embankments and support of structures applications requires designs that provide adequate bearing capacity and/or uplift capacity, tolerable settlement, and reduced liquefaction potential. Slope stability applications may require a ground modification design that provides specified minimum shear strength and reduces the liquefaction potential.

In general, analysis and design approaches are similar for stone columns and rammed aggregate columns. For both methods, design procedures are available in *Ground*

Modification Methods and *Geotech Tools*. Additional discussion and design examples can be found in Stone Column Design Manual and the Geopier manual.

The main design parameters to be considered include:

- Limits of treatment area
- Depth of treatment
- Replacement ratio
- Pattern of column layout
- Column diameter
- Column spacing

The effectiveness of ground treatment design is verified by in-situ geotechnical testing and/or load tests. In-situ geotechnical testing, such as CPT and SPT, are more appropriate where densification of the matrix soil is anticipated. Geophysical methods such as PS Suspension Logging and Full-Waveform Sonic Logging have been successfully used for verification of densification. Load tests usually provide more reliable verification. For both ground modification methods, verification load tests may include short-term test for ultimate bearing capacity, long-term test for consolidation settlement, and short-term horizontal shear test. Unique to rammed aggregate columns are modulus test and Bottom Stabilization Test (BST) (Fox and Cowell, 1998). The modulus test is essentially a plate load test to obtain the modulus of subgrade reaction of a test column. The BST is performed on top of the bottom bulb to verify that the column being installed has achieved general stabilization prior to the completion of installation. It is a method to determine whether a production column is comparable in quality to load test columns.

5.3.3 Reporting

The GDR should include sections that:

- Justify the use of a ground modification method, such as excessive predicted settlement, foundation bearing capacity failure, suspected liquefaction hazard, or slope instability.
- Justify the selection of stone column or rammed aggregate column method as the treatment strategy, including such considerations as constructability, cost, and effectiveness.
- Provide layout and cross sections of the ground modification area showing limits, pattern, spacing, and depths of the treatment columns, and supporting engineering calculations;
- Provide instrumentation and monitoring plans, and specifications (SSP and/or NSSP).

5.3.4 Considerations for Construction

A partial list of situations that may be encountered during construction include:

- Site clearance of underground and overhead utilities.
- Site accessibility for heavy equipment.
- Potential impact of ground movement, vibration, and noise to neighboring properties. Monitoring of the neighboring properties before, during, and after construction may be required.
- Difficult installation due to presence of rubble, concrete, abutment foundations, utilities, and other buried materials.
- For rammed aggregate columns, the presence of high groundwater combined with loose sandy material may cause caving of the drilled hole. Temporary casing may be needed to keep the holes stable.

In case the column verification testing fails to meet required performance criteria, consider adding more columns, increasing column depth, or adjusting column spacing.

5.3.4 Specifications

Non-standard specifications from previous Caltrans projects are available for both stone columns and rammed aggregate columns on Caltrans intranet. Contract specifications are also discussed in Ground Modifications Methods. In general, the specifications should include provisions on:

- Method specification (Materials, equipment, and construction procedure)
- Performance specification and acceptance criteria
- Verification testing
- Ground movement, vibration, noise control, and monitoring
- Field Inspection

6.0 References

1. *Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform*, SHRP2 Renewal Research, Transportation Research Board.
2. *Geotech Tools, Geo-Construction Information and Technology Selection Guidance for Geotechnical, Structural, and Pavement Engineers*, SHRP2, Transportation Research Board
3. *Ground Modification Methods*, Reference Manual Volume I and II, FHWA NHI-16-027 and FHWA NHI-16-028, April 2017
4. Barksdale, R. D., and Bachus, R. C., 1983, *Design and Construction of Stone Columns – Vol. I*, Federal Highway Administration, FHWA/RD-83/026.
5. Elias, V., Welsh, J., Warren, J., and Lukas, R., 2000, *Ground Improvement Methods Demonstration Project 116*, Federal Highway Administration, FHWA-SA-98-086.
6. Kimmerling, R. E., 1994, *Blast Densification for Mitigation of Dynamic Settlement and Liquefaction*, WSDOT Research Report WA-RD 348.1, 114pp.
7. Lukas, R. G., 1995, *Geotechnical Engineering Circular No. 1 – Dynamic Compaction*, Federal Highway Administration, FHWA-SA-95-037.
8. Mitchell, J. K., 1981, Soil Improvement: State-of-Art Report, proceedings of the 10th International Conference on Soil Mechanics and Foundation Engineering, Stockholm, Sweden, pp. 509-565.
9. Rixner, J. J., Kraemer, S. R., and Smith, A. D., 1986, *Prefabricated Vertical Drains – Vol. I: Engineering Guidelines*, Federal Highway Administration, FHWA/RD-86/168.
10. *Guideline and Recommended Standard for Geofoam Applications in Highway Embankments*, NCHRP Report 529, Transportation Research Board, 2004.
11. *Guidelines for Geofoam Applications in Slope Stability Projects*, National Cooperative Highway Research Program, Transportation Research Board, 2011.
12. *Foundation and Soil Reinforcement Manual*, Geopier, 1998

Appendix

(from 2014 version)

Ground Improvement Methods Used by Caltrans

Method	Dist-Co-Rte	PM	Date	EA	Purpose	Information Available
Wick Drains	01-MEN-101	43/51	2010-2014	01-26200	Embankment	GDR
Wick Drains	10-SJ-12	0.2/6.8	2007-2013	10-0A840	Embankment	GDR
Wick Drains	11-SD-005	(missing data)	2002	11-0301U	Embankment	GDR, Plans, Calculations
Wick Drains	04-Sol-37	8.0/10.5	(missing data)	04-0T1411	Embankment	GDR, Plans, Calcs, Spec
Wick Drains	04-CC-680	35/36	1999	04-006091	Embankment	GDR, Plans, SSP
Lightweight Fill-Cell Concrete	04-CC-680	38/39	1998	04-254504	Embankment	GDR, Plan, SSP
Lightweight Fill-Cell Conc./EPS	04-CC-680	38/40	2002	04- 006054	Embankment	GDR, Plan, SSP
Lightweight Fill-Cell Concrete	04-CC-680	38/39	2007	04- 0060A4	Embankment	GDR, Plan, SSP
Lightweight Fill – EPS	01-Men-101	37.7/39.6	2000-2002	01-293501	Embankment	GDR, Plan, Specs
Lightweight Fill - EPS	01-Men-101	35.6/38.9	2008-2009	01-474001	Slide Repair	GDR, Plan, Spec
Lightweight Fill – TDA	01-Men-101	98.5/100.9	2005-2010	01-397511	Embankment	GDR, Plan Spec
Lightweight Fill – TDA	08-Riv-215	(missing data)	2008	(missing data)	Retaining Wall	Ret Wall backfill
Lightweight Fill-Natural and expanded shale	04-Ala-80 Emeryville	(missing data)	(missing data)	(missing data)	Emb. & MSE	GDR, Plan, SSP
Lightweight Fill-Geogrid	04- ALA-80 Frontage Rd	(missing data)	(missing data)	(missing data)	Emb. & RSP	(missing data)
Lightweight Fill-Geogrid	04- Son-116	13.7	(missing data)	(missing data)	Slide Repair	(missing data)
Lightweight Fill-Geogrid	04-SON-116	40/41	2001	04-1S0601	Slide Repair	GDR, Plan, SSP
Lightweight Fill-Cell Concrete/MSE	SCL-87	11/13	2000	04-4874R1	Embankment	GDR, Plan, SSP
Lightweight Fill-Cell Concrete	04-Mrn-101	7.4	2009	04-4S5501	Embankment	GDR, Plan, SSP
Lightweight Fill-Cell Concrete	04-SF-101	8.0-9.8	2008	04-163701	Embankment	GDR, Plan, SSP
Lightweight Fill-Geogrid	04-SON-1	20.8-1.2	1998	04- 196461	Slide Repair	GDR, Plans, SSP
Lightweight Fill-Geogrid	04-SON-1	27.0	(missing data)	(missing data)	Slide Repair	GDR, Plans, SSP
Lightweight Fill-Terramesh	04-SON-1	26.5	(missing data)	(missing data)	Slide Repair	GDR, Plans, SSP
Lightweight Fill-Soldier Pile wall	04-SON-1 Miller Creek	40.1	(missing data)	(missing data)	Soldr Pile wall Slide Reapai	GDR, Plans, SSP
Lightweight Fill-Soldier Pile wall	04-NAP-128	(missing data)	(missing data)	(missing data)	Soldr Pile Wall Slide Repair	GDR, Plans, SSP
Lightweight Fill - Geogrid	04-SON-116	13.7	(missing data)	(missing data)	Slide repair Temp Wall	GDR, Plans, SSP
Stone Column-Liquefaction	04-ALA-260	1.1-1.7 (KP)	2000-2002	04-44010	Embankment	Seismic retrofit report
Stone Column-Slope Stabilization	SF-001	6.0-9.7	2011	04-1A9021	Embankment	GDR, Plan, SSP

Method	Dist-Co-Rte	PM	Date	EA	Purpose	Information Available
Stone Column-Slope stabilization	04-ALA-580	4.9-8.9	2010	04-4A0701	Embankment	GDR, Plan, SSP
Stone Column-Liquifaction	11-SD-005	(missing data)	2002	11-0301U	(missing data)	GDR, Plans, Calculations, Spec, QA results
Rammed Aggregate Piers-Embankment and RW	SON-101Airport Blvd	(missing data)	2013	04-3A23U1	Appr. Emb Ret. wall	GDR, Plan, SSP
Rammed Aggregate Piers	MRN/SON-101	(missing data)	2014	04-264091	Embankment	GDR, Plan, SSP
Compaction Grouting	SCL-87	7.5	2007	04-930322	Sink hole/ settlement	GDR
Compaction Grouting	SCL-87	4.84	2007	04-4396U4	Sink hole/ settlement	GDR
Compaction Grouting	SCL-880	2.0/ 2.1	2010	(missing data)	Sink hole/ settlement	Grouting Plan
Compaction Grouting	SON-1	10.4	2008	04-4S3604	Settlement	GDR/FR
Compaction Grouting	07-LA-105	(missing data)	2004	07-18830	(missing data)	GDR, Plans, Calculations, Spec
Compaction Grouting	07-LA-091	(missing data)	2005	07-18220	(missing data)	GDR, Plans, Calculations, Spec, QA results
Permeation Grouting	07-LA-213	(missing data)	2003	07-4L020	(missing data)	Specifications
Jet Grouting	Oakland	(missing data)	2003	Pose/ Webster Tube	Fill Voids	Consultants- Liu done Inspection
Jet Grouting	04-ALA-260	1.1-1.7 (KP)	2000-2002	04-44010	Fill Voids	Seismic retrofit report
Injected Lightweight Foam Fill	04-ALA-580	43.2	2012	04-1F3903	Fill Voids	(missing data)
Injected Lightweight Foam Fill	04-ALA-680	0.9-1.6	2013	04-4G7003	Fill Voids	(missing data)
Injected Lightweight Foam Fill	04-CC-80	(missing data)	(missing data)	(missing data)	Fill Voids	(missing data)
Injected Lightweight Foam Fill	CC-4	5.4	2012	04-2G6504	Fill Voids	GRD/ Plan
Injected Lightweight Foam Fill	SCL-85	0.27	2010	04-4S0601	Fill Voids	GDR/Plan
Injected Lightweight Foam Fill	SON-128	5.4	2010	(missing data)	Fill Voids	GDR/Plan
Injected Lightweight Foam Fill	SOL-680	11.9	2010	04-1F6404	Fill Voids	GDR/Plan
Deep Mixing	04-SF-101	8.0-9.8	2008/ present	(missing data)	Embankment	GDR, Plan, SSP
Deep Mixing	04-SON-101	4.0-5.2	2009	(missing data)	Embankment.	GDR, Plan, SSP

Method	**Dist-Co-Rte**	**PM**	**Date**	**EA**	**Purpose**	**Information Available**
Micropiles	01-Hum-101	111.5	2010-2011	01-488303	Slide repair	Plan
Micropiles	Son-1	21.7	1995	04-193961	Slide repair	GDR, Plan, SSP
Micropiles	Son-1	21.5	2001	04-1S2801	Slide repair	GDR, Plan, SSP
Micropiles	04-92/280	10.2	2011	04-1A7701	(missing data)	GDR, Plan, SSP
Micropiles	07-LA-027	(missing data)	2001	07-45460	(missing data)	GDR, Plans, Spec