COMMENTARY GUIDELINES
For
GROUND IMPROVEMENT
Using
DISCRETE ELEMENTS

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Prepared by

Seattle Section Geotechnical Group of the American Society of Civil Engineers and the City of Seattle Department of Construction and Inspections

Commentary Guidelines for Ground Improvement using Discrete Elements

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Section 1

INTRODUCTION

This document presents results of a request to evaluate common approaches for ground improvement design as it relates to the use of ground improvement to mitigate against liquefaction and/or to improve Site Class. The purpose of this document is to provide commentary guidelines that address concerns regarding the disparity among common approaches for ground improvement design and design recommendations submitted to the City of Seattle Department of Construction and Inspections (SDCI) in support of construction permit applications.

The development of ground improvement commentary guidelines is the result of a collaborative effort between the Geotechnical Group of the Seattle Section of the American Society of Civil Engineers (ASCE) and SDCI. The committee was open to all interested parties and included engineers representing small, medium and large-sized geotechnical engineering firms in private practice, geotechnical specialty contractors, university professors and staff from SDCI.

This document addresses the geotechnical design aspects of discrete elements, regardless of shape (circular, square, octagonal, etc.), regardless of stiffness (compacted aggregate piers, cemented aggregate piers, unreinforced concrete/lean mix concrete, etc.) and not in contact with each other. It is understood that there are many forms of ground improvement (e.g. preloading, soil freezing, soil mix panels/grids, earthquake drains, etc.) which may or may not be appropriate for a particular application at a particular site. These other ground improvement techniques are not specifically addressed in this guidance document.

As noted above, this document is the result of a request to evaluate ground improvement design as it relates to the use of ground improvement to mitigate against liquefaction and/or improve Site Class. During the development of this document it became clear that the SDCI and the geotechnical community would benefit from comments and guidance for static design. Therefore this document primarily addresses seismic issues (e.g. liquefaction, Site Class, bearing capacity, settlement, etc.) and in some cases addresses static issues. The members of the committee agree that when recommending or designing ground improvements for static conditions the literature is consistent and design methods are well established. Therefore this document does not provide technical guidance for static design.

In addition to this introduction, this document is divided into the following sections:

Section 2 summarizes some of the technical aspects of ground improvement design. Section 2 includes a technical discussion regarding the recent research associated with the use of the "reinforcement mechanism" of ground improvement as it relates to seismic design. Section 2 also comments on the use of ground improvement to change the Site Class of a proposed structure and when third party peer review may be required by the permitting authority.

Section 3 provides ground improvement designers with the minimum information that should be conveyed in the design calculations and plan sheets submitted to a code enforcement agency for issuance of a building permit. Section 3 also provides SDCI with a reference document for use when reviewing ground improvement designs. Section 3 specifically addresses the items to be included in the ground improvement design calculation package, information to be contained in the on the ground improvement plan sheets and addresses issues related the "Geotechnical Engineer of Record".

Section 4 provides geotechnical engineers with a framework to consider in preparing geotechnical engineering reports that recommend ground improvement for static and/or seismic loading conditions to increase bearing capacity, reduce settlement, improve slope stability, and or limit lateral spread mitigation. Section 4 also provides a code enforcement agency with a current state of practice reference document for reviewing geotechnical reports that recommend ground improvement. It is understood that not all of the recommendations are applicable to every project or every type of ground improvement due to the specific needs of an individual project and the specialized nature of the various ground improvement techniques.

Section 5 provides a list of references used to develop these commentary guidelines. To avoid confusion, ASCE and SDCI have opted not to include references that provide recommendations for the reinforcement mechanism based on strain-compatibility assumption (pure shear). See Section 2 for more information.

The various sections of these commentary guidelines sections assume the user is familiar with all the other sections. In particular, a ground improvement design engineer is expected to have a working knowledge of all aspects of Sections 2 and 3. A geotechnical engineer providing design recommendations for ground improvement is expected to be familiar with the requirements and technical considerations of Sections 2 and 3 when developing the design recommendations called for in Section 4 of these commentary guidelines.

The purpose of these commentary guidelines is to improve quality and consistency of ground improvement related submittals submitted to a code enforcement agency. The Committee developed this document with the understanding that it would likely be used as the basis for establishing or modifying Director's Rules or polices regarding minimum standards for ground improvements using discrete elements related submittals provided to a code enforcement agency in support of construction and land use permits. The committee also recognizes that others (owners, ports, municipalities, etc.) not directly involved with the development of these commentary guidelines, may use this document to improve quality and consistency of ground improvement submittals they receive. Users of this document should rely on the entire document, relying only on Sections 3 and 4 might result in omission of important technical issues.

Section 2 (Technical Commentary)

In order to address the disparity in the shear-strain compatible design approaches, this section of these commentary guidelines provides a commentary on recent studies and advancements in ground improvement design with discrete elements for liquefaction risk mitigation. The goal of the technical commentary is to highlight the findings of the recent studies on this matter. The technical commentary does not intend to define suitable methods or design equations for ground improvement design in potentially liquefiable soils. Rather, this commentary provides a brief discussion of the findings of the recent studies on ground improvement design with discrete elements for liquefaction risk mitigation focusing on the assumptions of strain compatibility and composite shear stiffness. A list of available references that address shear and flexure for discrete element design is provided in Section 5.

The initial studies that once formed the basis for the reinforcement mechanism of ground improvement for liquefaction risk mitigation assumed shear-strain compatible deformation, where both the discrete elements and the potentially liquefiable surrounding soil were assumed to deform in pure shear during ground shaking. The strain compatible deformation caused Cyclic Shear Stresses (CSR) to be diverted to the stiffer discrete elements while significantly reducing the CSR acting on the potentially liquefiable soil between the discrete elements through shear-strain deformation. However, more recent studies have indicated that during ground shaking, the discrete elements deform in a combination of shear and flexure. Combined shear and flexure deformation results in higher CSR demand when compared to the CSR demand calculated using pure shear (no flexure) deformation.

As discussed above, the scope of this section is limited to discussion of discrete elements, regardless of shape (circular, square, octagonal, etc.), regardless of stiffness (compacted aggregate piers, cemented aggregate piers, unreinforced concrete/lean mix concrete, etc.) and not in contact with each other and used for the mitigation liquefaction. The committee recognizes that there are many forms of ground improvement (e.g. preloading, soil freezing, soil mix panels/grids, earthquake drains, etc.) which may or may not be appropriate for liquefaction mitigation. These other ground improvement techniques are not specifically addressed in this guidance document.

Liquefaction Mitigation Mechanisms

Ground improvement by discrete elements can mitigate liquefaction risk primarily through one or combination of three mechanisms: (1) densifying the soil mass, (2) dissipating excess pore pressures, and (3) reinforcing the soil mass. The extent of mitigation which is possible by each of the three mechanisms depends on the soil materials and the methods used for ground improvement.

(1) Densifying the soil mass

In loose cohesionless soils, densifying the soil between discrete columns installed by displacement methods (e.g., stone columns, displacement aggregate piers, and displacement piles) has been widely recognized as a means of improving liquefaction resistance. The degree of densification depends on the:

- Mineral properties of the granular material,
- Quantity and properties of the fine-grained material in the soil deposit,
- Initial stress state of the deposit,
- Energy applied during densification, and
- Ability of the deposit to dissipate excess pore pressures generated during densification (by natural or engineered drainage).

The increased density of the treated soil can be verified by in-situ field testing (such as the Cone Penetration Testing [CPT], Standard Penetration Testing [SPT], non-composite Shear Wave Velocity (Vs) testing, and others at locations midway between the installed elements. Testing of the discrete elements themselves does not verify the densified state of the composite improved ground. Research testing methods that can measure increases in the composite ground stiffness have been developed, but these are not readily available for commercial use.

(2) Dissipating excess pore pressures

The drainage mechanism of aggregate discrete elements (e.g., stone column or aggregate piers) may enhance dissipation of excess pore water pressure during ground shaking in potentially liquefiable ground. Studies show that the effectiveness the discrete columns is affected by the permeability of the in-situ soil, the spacing of the discrete elements, and the intermixing of columns with surrounding soil, and other issues. Thus, liquefaction risk mitigation through excess pore water dissipation from discrete aggregate columns is not widely used in US practice. It is suggested that the drainage mechanism associated with aggregate discrete element improvement should be relied upon only if site-specific pre-construction and post improvement field permeability testing is conducted to verify drainage assumptions.

(3) Reinforceming effects

Reinforcement can improve liquefaction resistance by redistributing some of the Cyclic Shear Stresses (CSR) from the unimproved soil to the stiffer discrete elements. Shear stress redistribution mechanism is based on the assumption that the discrete elements are stiffer than the surrounding soil and therefore attract more of the seismic shear stress, thereby reducing the shear stress in the surrounding soil. In silty sand, clayey sand and fined grained soils, densification and drainage are difficult to achieve, reinforcement provides the primary mechanism for mitigating liquefaction.

For the shear stress redistribution mechanism, early studies assumed that the discrete elements and the surrounding soil deformed equally in pure shear, i.e., shear-strain compatible deformation. The shear strain compatible deformation assumption allowed substantial reductions in the CSR. However, research within the last two decades has shown that discrete elements deform in a combination of shear and flexure, and the relative contribution to deformation by flexure and shear varies with depth. The CSR redistribution from the soil to the discrete element is governed by the mode of deformation; accordingly the CSR redistribution initially developed with the assumption of pure shear deformation of the soil and discrete elements can predict higher shear stress reductions (i.e. lower CSR in surrounding soil) than those shown in recent studies which account for a combination of shear and flexure deformation.

The shear strain compatible deformation approach is widely used; however, current research recommends against the use of shear strain compatible design methods for ground improvement design with discrete elements and recommends methods considering shear and flexure modes of deformation.

Site Response as Modified by Ground Improvement

The seismic demand assumed to be applied to a soil site during strong ground motion can be estimated by various methods depending on the intended use. For liquefaction analysis, the seismic demand is generally computed using two common approaches: simplified shear beam methods (e.g. Seed and Idriss 1971, Youd et al 1997, Idriss and Boulanger 2008, among others), or one-dimensional (1-D), site-specific site response analyses. For the development of ground surface response spectra used by structural engineers, the demand is generally computed using 1-D, code-based procedures for general soil conditions or 1-D site-specific site response analysis. Each of these seismic demand estimation methods assumes pure-shear soil behavior. Installation of ground improvement elements will result in some level of change to the site's ground motion characteristics. Owing to three-dimensional (3-D) ground improvement element geometry, the dimensional extent of ground improvement, and the known development of flexure during shaking, the modeling of ground improvement elements in one-dimensional site response analyses comprises a violation of assumptions invoked. The resulting error in site response estimation and corresponding engineering implications likely vary from project to project, depend on local site conditions, and the dimensions and details of the ground improvement. Unfortunately, there are no currently-accepted practices or guidelines in the framework of 1-D pure shear site response methods for approximating the seismic site response resulting from the use of ground improvement elements.

Changing Site Class via the densification or drainage mechanisms should be performed in accordance with ASCE 7 and verified via post improvement testing of the improved soil (not the discreet elements). Changing Site Class via the reinforcement mechanism is complex. The project team should anticipate the permitting authority will require third party review.

Comments Regarding Permitting Authority Review

Ground improvement design to resist seismic loading in liquefiable soils is a complex process that differs with performance criteria for the structure and the subsurface conditions. Designers must realize that it may not be possible to completely eliminate seismic liquefaction by reasonable application of any discrete ground improvement technique in some subsurface conditions. This is not to say that ground improvement with discrete elements cannot be a viable method of foundation support with liquefied soil surrounding the elements, but the design must recognize that condition. Recognizing that liquefaction elimination may not be possible may also drive the design to a completely different type of foundation support than ground improvement by discrete elements.

For these reasons, a code enforcement agency may require third party review of the seismic site response induced by the ground improvement design before issuance of a building permit if a site class change due to ground improvement by reinforcement is claimed. Designers are encouraged to discuss the intent of a site class change early in the design process with the building official to reduce the impacts to the project if a peer review will be required.

Section 3 (Design Submittals)

Introduction

The guidance herein has been developed to provide ground improvement designers with the minimum information that should be conveyed in the design calculations and plan sheets submitted to a code enforcement agency for issuance of a building permit.

Ground Improvement Design Calculation Package

The ground improvement design calculations should include the following:

- Design response spectrum (or Site Class) for unimproved ground conditions at the site from the Geotechnical Report in accordance with the applicable design code (e.g. ASCE 7, IBC, etc.).
- If the ground improvement design changes the site's ground motion response (Site Class), such change should be supported by evaluations appropriate for the methods of improvement (e.g. densification, drainage, reinforcement) as follows:
    - Changing Site Class and/or dynamic site response via the densification or drainage mechanisms should be verified via post improvement testing of the improved soil (not discrete elements). The improved Site Class should then be evaluated as required by ASCE 7 using the results of the post improvement testing via either:
        - The project team should anticipate the code enforcement agency will require the anticipated post improvement site class be achieved before an occupancy permit will be issued, or
    - Changing Site Class and/or dynamic site response via the reinforcement mechanism is complex. If the reinforcement mechanism prevents liquefaction, the improved Site Class cannot be higher than the non-liquefied Site Class without the consideration of the reinforcement's stiffness and strength. The project team should anticipate the permitting authority may require third party review. The project team should anticipate the need to perform either:
        - Dynamic soil-structure interaction analysis that considers the three-dimensional nature of the specific ground improvement being utilized, or
        - Site-specific site response analyses performed with post-improvement dynamic soil properties obtained from verification testing of either the weakest portion of the three-dimensional improved ground structure

(e.g., testing midway between discrete elements). (Code based determination based on composite shear wave velocity ($V_{S,30}$), composite strength, and/or composite density are not acceptable.)

- Change of a site's ground motion response should be supported by verification testing of either the weakest portion of the 3-dimensional improved ground structure (e.g., testing midway between discrete elements).
- Clear indication of which references are being followed for the design calculations and that they are in accordance with the design methods recommended in the Geotechnical Report.
- Area of improvement.
- Type of ground improvement: Identify the length to diameter ratio of the improvement elements, if applicable.
- Design assumptions: Clearly indicate design assumptions for the suggested ground improvement method:
    - To what extent the design considers shear/flexure strain compatibility under seismic conditions.
    - Whether the soil between the ground improvement points is expected to liquefy or otherwise undergo a reduction of strength.
- Post treatment testing program: If the design relies on changes to the in situ soil density, provide a post treatment testing program to specify allowable types of tests, and their frequency, depth, and required results.
- Liquefaction potential: State the liquefaction analysis method used and provide a factor of safety verses depth plot for the pre-improvement and post improvement conditions. Excess pore pressure ratio, R_u, may be used in lieu of factor of safety. This plot should extend to the bottom of the potentially liquefiable layer and in no case should be less than the soil profile thickness used for determination of Site Class.

Ground Improvement Plan Sheets

The ground improvement plan sheets should clearly indicate the following:

- Number & location of ground improvement elements.
- Depth (or embedment into bearing layer) and diameter of ground improvement elements.
- Extent or lack thereof of treatment beyond building perimeters.
- If the ground improvement design considers different replacement ratios for different loading conditions/areas (e.g. footings, slab on grade, treatment outside the building footprint, paved areas, etc.), they should be noted clearly on the plan sheets.

Geotechnical Engineer of Record

In the event that the ground improvement design or an amended ground improvement design is submitted and stamped by an engineer other than the Geotechnical Engineer of Record, it shall be accompanied by a signed and stamped letter indicating that the Geotechnical Engineer of Record has reviewed the ground improvement design and finds it in conformance with the geotechnical report for the project.

In the event that the submission of the ground improvement design is accompanied by a change in the geotechnical engineer of record, the Owner shall notify the code enforcement agency of the change in writing in accord with the requirements of the code enforcement agency (in Seattle Director's Rule 5-2016 or subsequent rules).

Section 4 (Geotechnical Engineering Reports)

This portion of the commentary guidance is intended to:

1. Provide geotechnical engineers with a framework to consider in preparing geotechnical engineering reports that recommend ground improvement for static and/or seismic loading conditions to increase bearing capacity, reduce settlement, improve slope stability, and or limit lateral spread.
2. Provide the code enforcement agency with a current state of practice reference document for reviewing geotechnical reports recommending ground improvement.

While these commentary guidelines address the use of ground improvement to mitigate the effects of soft or liquefiable soils under both static and dynamic/seismic transient loading conditions, it is recognized that much of the ground improvement being considered in the City of Seattle is for the mitigation of seismic hazards to reduce the risks of building collapse.

Furthermore, the framework is intended to be neutral towards the actual ground improvement techniques, concepts, and methods, which are often specialized, in development or proprietary. It is generally good practice to consult with local specialty contractors during preparation of the site-specific ground improvement recommendations to confirm the suitability of the site and the availability of equipment especially on more unique projects.

Not all of the following recommendations are applicable to every project or every type of ground improvement due to the specialized nature of the various ground improvement techniques. The intent of this guidance is to provide a framework of topics that should be considered in the preparation of a geotechnical report which recommends ground improvement so the designer has the appropriate information to develop a design which meets the minimum performance levels required for the structure and provides the code enforcement agency with sufficient information to review that design during permitting of the project.

There is also some overlap between these geotechnical report commentary guidelines and the design commentary guidelines provided in Section 3. This overlap reflects the need for a geotechnical report to verify at that there is at least one workable solution prior to permitting, but recognizes the condition that final design of ground improvement may be completed by a specialty designer/contractor and differ in the means by which the performance criteria are achieved.

Performance Requirements

The geotechnical report recommending site specific ground improvement should explicitly define the performance criteria and requirements for the improved ground based on defined loading and design criteria. The recommendations must clearly indicate whether the design intent of the ground improvement is to increase bearing capacity, reinforce the soil, perform as a structural element, and/or mitigate seismically induced settlement/deformation.

As the ground improvement program moves from recommendations through design and permitting, it should be a collaborative effort with other professional disciplines and the performance requirements should be expected to evolve. Any subsequent changes to the performance requirements contained in the geotechnical data report should be addressed and communicated to the code enforcement agency as an addendum to the original geotechnical report.

The report must clearly indicate the tolerable settlement, the required factor of safety for bearing capacity and/or slope stability for static and/or seismic loading conditions, and site class improvement for building seismic design.

Allowable Bearing Pressures and Loads

Ground improvement recommendations should identify the allowable bearing pressure(s) that must be achieved by the improved ground. The specification should define:

1. How the allowable design bearing pressure is to be computed
    a. Is the controlling criterion based on a minimum Factor of Safety or on a serviceability/settlement requirement?
    b. At what location is the target bearing pressure to be computed?
        i. Average across foundation/earth structure?
        ii. At extreme foundation edge?
        iii. Is the bearing pressure constant across the bottom of the footing?
    c. Are there distinct requirements for footings (isolated or continuous), grade beams, mats, slabs, mechanically-stabilized earth, retaining walls, etc.?
    d. Specific loading conditions for each distinct loaded element.

Settlement/Displacements

Recommendations should include the allowable ground deformations following ground improvement installation. Criteria are likely to vary by structure and foundation type and may be different for different project components. Project components may include:

1. Continuous footings
2. Isolated footings and/or mat foundations
3. Slabs-on-grade
4. Pavements
5. Utilities
6. Tanks
7. Embankments
8. Retaining walls, ect.

Ground deformation recommendations should consider the following items:

1. Allowable total and differential settlement for static conditions.
2. Allowable total and differential settlement for seismic conditions.
3. Allowable lateral spread displacements.
4. Minimum FoS for static and seismic slope stability.
5. The conditions for which settlement computations are to be performed
    a. Provide allowable bearing pressures which are to be used in the ground improvement design to calculate anticipated settlements.
    b. Define the acceptable levels of settlement in relation to both magnitude and time.
        i. Immediate / during construction settlement
        ii. Primary consolidation settlement
        iii. Secondary compression / creep settlement.

6. Define where and how settlement is to be measured (If applicable).
   a. Monitoring precision required.
   b. Location of settlement monitoring.
      i. Composite – measure settlement of the combined system
      ii. Unimproved Ground – measure settlement in between ground improvement elements
      iii. Element – measure settlement of ground improvement elements
   c. Equipment/methods of monitoring.
      i. Monuments,
      ii. PK nails,
      iii. settlement plates,
      iv. vibrating wire devices,
      v. robotic monitoring,
      vi. LiDAR, etc.
7. Schedule for monitoring / measurement to occur.
   a. During construction
   b. Post-construction
      i. Following ground improvement?
      ii. Following substantial completion of structure?
   c. Frequency and duration.
8. What is the reference baseline?
   a. Will the reference baseline be impacted by seasonal or cyclic changes (e.g., tidal fluctuations, passage of vehicles)

Seismic Considerations

At a minimum, the geotechnical report with ground improvement design recommendations should include the following items:

1. The performance criteria for the ground improvement (e.g. limit static settlement in loose soil above the groundwater, mitigate liquefaction, prevent liquefaction, mitigate lateral spread, mitigate slope instability, improve site class, etc.)
2. A description of the design earthquake criteria and/or input ground motion:
   a. The reference/source of the ground motions.
   b. Note if a site-specific seismic hazard analysis is included, will be provided, or may be performed by the ground improvement designer.
   c. Dynamic response spectrum:
      a. Code-based response spectrum based on the Site Class for the pre-improvement condition,
      b. Code-based response spectrum based on the anticipated Site Class for the post-improvement condition (applies only to the densification and drainage mechanisms),
      c. A detailed site response study,
   d. The seismic design parameters including peak ground acceleration (PGA), short and long period spectral accelerations (Sa_S and Sa_{1s}), the corresponding horizontal ground acceleration coefficient, and corresponding moment magnitude (Mw) from the deaggregation analyses.
3. The design ground water depth/elevation to be used for liquefaction analysis. It is recognized that this ground water elevation is not necessarily the elevation at which

groundwater was encountered nor is this elevation the level to be used for static design or at which ground water is expected to be encountered during construction.

4. The minimum depth and horizontal limits required for liquefaction mitigation. The report should specifically comment on:
    a. The need for elements outside of the building footprint and
    b. Options for when the distance between the structure and the limits of construction (e.g. a property line) is limited.
5. The minimum thickness of potentially liquefiable layers.
6. If the intent of the ground improvement includes modifying the site response (or improving the Site Class for a code spectrum), then specify the post ground improvement target design response spectrum (or the improved Site Class) and verify at least one ground improvement method is capable of achieving this improvement.
7. Identify the analytical method(s) that is/are used for the following:
    a. Differentiating sand-like from clay-like behavior during ground motion
    b. Considering the shear/flexure strain compatibility between ground improvement elements and the unimproved existing soil or the improved existing soils. Pure shear strain compatibility is unacceptable.
    c. Determining liquefaction potential
    d. Determining seismic settlements.
    e. Estimating lateral spread.
    f. Dry sand dynamic settlement.
    g. Modifying the site response
8. Describe the allowable (feasible) ground improvement techniques (all, some, or none of the following):
    a. densification
    b. discrete reinforcement
    c. accelerated drainage and surge relief
9. Identify pre-treatment testing and/or post-treatment verification testing requirements.

Site Class Changes

If one of the intents of the ground improvement includes modifying the site response, there are several considerations which the geotechnical report should address. Because of the schedule risk associated with designing a structure based on site class changes in those cases where the ground improvement does not achieve the required improvements, it is imperative that the Owner recognize those risks and that the intent to change the site class is brought to the attention of the code enforcement agency at a pre-submission meeting.

Chapter 20 of ASCE 7-10, which describes how a seismic site class is determined, can be considered for application to sites where ground improvement is used, with some limitations. The initial site class should be determined based on the unimproved soil and groundwater conditions. As with all potentially liquefiable sites, the evaluation starts with the determination of Site Class F status. Note that the evaluation for Site Class F does not include the calculations of Vs30 or any other parameter in Section 20.4. If ground improvement is used, a redetermination of site class can be made based solely on the soil and groundwater behavior as modified by ground improvement elements, noting the exceptions described below. Modified soil behavior should be estimated based on engineering calculation and subsequently verified in the field following construction.

If the conditions for Site Class F do not apply then the remaining site classes are evaluated based on the procedures and calculations for the remaining sections of Chapter 20 using the modified soil parameters. The seismic site response of an improved site is complex and there is a lack of definitive research or consensus on the subject. The finite, dimensional extents and 3D configuration of most ground improvement designs and the 3D response of the soil likely prevents 1-D, free-field conditions from being achieved. To address these limitations, the geotechnical engineer may use other analytical methods for site response calculation that are not constrained to the pure shear and/or one-dimensional assumption in order to include the influences of the ground improvement design on site response. Shear strain compatible composite site parameters based on composite soil and ground improvement parameters are not appropriate.

For these reasons, the building official may require third party review of the pre- and post-improvement seismic site response before issuance of a building permit. Designers are encouraged to discuss the intent of a site class change early in the design process with the building official to reduce the impacts to the project if a third party review will be required.

Additional information may be found in DFI Journal No.7, August 2013. Specifically, the articles *Commentary on the Selection, Design and Specification of Ground Improvement for Mitigation of Earthquake-Induced Liquefaction by the Ground Improvement Committee and Liquefaction Mitigation Synthesis Report* by Timothy C. Siegel are particularly relevant.

Verification

Not only are the project baseline references and performance requirements important to a well-conceived ground improvement recommendation, but also the means and methods for verification of improvement are essential. These verification tools must be consistent with the specified analytical and design methods, ground improvement technology and soil conditions. Therefore, the specification should clearly define:

1. Acceptable methods for verification testing
    a. In situ testing
        i. Penetration tests
        ii. Static load-deformation tests
        iii. Shear wave velocity measurements
    b. Acceptable methods for field sampling and laboratory testing
        i. Sampling
        ii. Handling, storage, curing, etc.
2. Quality control measurements during installation
3. Data acquisition requirements
    a. Field reporting requirements
    b. Field instrumentation requirements
4. The frequency and schedule for any such testing
    a. Is/are pre-production test element(s)/section(s) appropriate or required?
5. Minimum or maximum verification requirements or requirements for average values and acceptable ranges/variation.
    a. Will a statistical approach be utilized, e.g., the average value must meet or exceed the requirement but no individual value may be less than 10% lower than the requirement.
6. Parties responsible for verification testing

7. Parties responsible for review and approval of verification testing.

Special Circumstances

Many projects include special site characteristics that may have a significant impact on successful implementation of specific ground improvement methods and should be highlighted in the ground improvement recommendations.

Special considerations that must be addressed include:

1. Obstructions: Many ground improvement tools are ill-suited to penetrate or bypass significant buried masses. Likewise, anticipated natural obstructions should also receive comment. A concrete block and a granite boulder each represent similar challenges to ground improvement equipment. The document should comment on the existence or potential for man-made, underground obstructions to be present.
2. Flowing and artesian water conditions: Often overlooked is the potential for artesian pressure or significant subsurface gradients/groundwater velocity to negatively impact ground improvement methods, specifically grouting and ground freezing techniques. The specification and data report should identify the potential for these conditions.
3. Hazardous materials: The presence or potential presence of hazardous materials or gases (e.g., methane, hydrogen sulfide, etc.) must be disclosed in the contract documents. Under many circumstances, ground improvement techniques are the appropriate solution to mitigate risks associated with such conditions, but the potential bidders must fully understand the project environment to prepare a responsive proposal.

Section 5 (References – Recent Works)

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