Advances in California - Ground Improvement Support of Heavy Foundations

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Abstract

Ground improvement has been used extensively in the western United States in recent decades to support heavy foundations, to increase soil stiffness and bearing capacity, to control static and seismic settlement, and to reduce the damaging effects of soil liquefaction. With recent changes in the California Building Code and evolving environmental regulations, engineers are relying more on specialty geo-contractors to provide deep foundations and stiff ground improvement systems to support heavy foundation loads with increased seismic demands. We aim to present agency-accepted ground improvement methods that have been used in California and advances in these methods to meet Code changes and regulatory demands in California with specific emphasis on the Drill Displacement Column™ (DDC) system.

This paper describes seismic events and changes to Code that have driven advances in engineering design in California, including recent developments and challenges of ground improvement techniques such as Drill Displacement Column™ and Rammed Aggregate Pier® technologies. Environmental conditions including noise and vibrations, contaminated soil sites, regional groundwater protection zones, and regulatory agency requirements, can often affect the design and delivery of ground improvement systems. The DDC system (a type of rigid inclusion and composite ground system) has received increasing attention in California due to the needs for environmentally safe ground improvement, higher bearing capacity below shallow foundations, reduction of soil off-haul, and no-vibration construction requirements in dense urban areas.

Structural considerations for foundation design are presented for Drill Displacement Column™ and Rammed Aggregate Pier® (RAP) systems. For example, in California, the DDC system offers strong, uniform support with very stiff ground improvement that requires specific engineering and construction considerations to eliminate footing hard points and that laterally disconnect the ground improvement from foundations and the mass lateral forces during seismic motion from the structure above. In addition, a summary of agency approvals will be presented for the DDC ground improvement system.

Code-changing Earthquakes in California

A large number of significant earthquakes have been documented by the United States Geological Survey (USGS) worldwide in the past decades (USGS Seismic Hazards Program, 2016). The USGS documents 92 large (Magnitude 6 and above) earthquakes in the western United States since the 1900s, which are mostly in California. Some of the historical earthquakes in California led to legislation and Code changes that have affected engineering design, acceptable foundations, and civil construction. Selected earthquakes and their impacts to codes and engineering practices are summarized below (California Seismic Safety Commission, 2000):

- San Fernando Valley Earthquake (February 9, 1971, Magnitude 6.6): This event resulted in 58 deaths, over 2,500 hospital-treated injuries, some freeway overpass collapses, and more than $500 million in damage. The San Fernando dam was nearly breached in this event and prompted considerable seismic liquefaction studies. This event prompted research and development of bridge seismic design, introduced ductility in concrete design, and prompted the passage of Alquist-Priolo Earthquake Fault Zoning Act of 1972, Hospital Seismic Safety Act of 1973, and the Strong Motion Instrumentation Program.

- Whittier Earthquake (October 1&4, 1987, Magnitude 5.9): These two events caused a total of 9 deaths, over 200 injuries, over 30 commercial buildings either razed or declared unsafe, hundreds of houses and apartments destroyed, and thousands of houses and apartments suffered major damage. Total financial damage due to these events was estimated to be approximately $358 million. These events caused cracks in the support columns at 605/I-5 interchange, and minor damage to 28 other bridges. Following the Whittier earthquake, the California legislature increased funding for Strong Motion Instrumentation Program and initiated earthquake insurance studies.

- Loma Prieta Earthquake (October 17, 1989, Magnitude 6.9): This event resulted in 62 deaths, 3,700 injuries, 963 homes destroyed, 18,000 homes damaged, 147 buildings destroyed, and 2,500 other buildings damaged. Total financial damage was over $10 billion; San Francisco alone suffered $2 billion in damage and prompted the legislation of the Seismic Hazards Mapping Act of 1990. Earthquake engineering research activities following this event has resulted in significant modifications to ground motions and increasingly stringent codes that affected engineering design and construction.

- Northridge Earthquake (January 17, 1994, Magnitude 6.7): This event resulted in 57 deaths, 9,000 injuries, and $20 billion damage. It prompted the legislation and formation of California Earthquake Authority in 1996. Considerable changes to Code have occurred since this earthquake including significant changes in ground motion evaluations, seismic regulations, and the development of more stringent codes starting with the 1997 Uniform Building Code (UBC) and the 2000 International Building Code (IBC), based on ASCE 7-02 and ACI 318-02.

Changes in Seismic Design Codes from ASCE 7-05 to ASCE 7-10

The current Minimum Design Loads for Buildings and Other Structures, ASCE 7-10, referenced in the 2012 and 2015 versions of the IBC, has replaced the earlier version, ASCE 7-05. The IBC model building code has been adopted, with modifications, by the California Building Standards Commission into its California Building Code (Susan Dowty, 2011).

Seismic design provisions have been transformed and have become more stringent from the ASCE 7-02 and ASCE 7-05 to the current design standard, ASCE 7-10. Significant changes were made to the seismic ground motion maps in ASCE 7-10 in several ways that affect geotechnical evaluations and ground improvement designs in California:

1. **USGS updates**: Next Generation Attenuation (NGA) relationships were used by USGS in the western United States, and excluded the old attenuation relationships.

2. **Risk-targeted ground motion**: Maximum Considered Earthquake (MCE) ground motion maps in ASCE 7-10 were based on a risk target of 1 percent in 50-year collapse (MCE_R), rather than a 2 percent probability of exceedance in 50 years in ASCE 7-05.

3. **Maximum-direction ground motion**: ASCE 7-10 maps now correspond to ground motion in a direction that produces the maximum structural response; whereas, the ASCE 7-05 maps corresponded to estimated ground motion of the geometric mean of two orthogonal components of motion at a site. The switch from geometric-mean ground motion to maximum-direction ground motion has resulted in increases in short-period ground motion by a factor of 1.1 and increases in long-period ground motion by a factor of 1.3.

4. **Modified deterministic ground motions**: In high seismicity regions, seismic hazard is generally governed by large-magnitude earthquakes from a few well-defined fault systems. Probabilistic ground motions may be larger than deterministic ground motions, depending on the characteristics of the governing faults. The MCE in ASCE 7-05 was based on 150 percent of median ground motions, whereas, the MCE_R in ASCE 7-10 is based on eighty-fourth-percentile ground motions, which increased median ground motions by 180 percent.

5. **Liquefaction potential evaluation**: Where ASCE 7-05 used the short-period spectral acceleration divided by 2.5 for Peak Ground Acceleration (PGA), ASCE 7-10 now bases evaluations of liquefaction potential on the geometric mean values, modified for site class effects using a site coefficient ($PGA_M = PGA \times F_{PGA}$).

These changes to seismic design code have influenced both the magnitude of structural loading and liquefaction related hazards, which affect the design and construction of structures, foundation systems, and ground improvement systems.

Regional Regulatory Requirements

"Real estate values in California have skyrocketed over the past several years since the 2009-2010 recession. California commercial real estate is booming once again and optimism about the future has not been dampened by the Fed's interest rate policy," (Allen Matkins and UCLA Anderson Forecast, 2016). Land values and desirable locations have given rise to commercial developer, public agency, and industrial entity's consideration of impacted sites and contaminated sites for vertical construction. One high-profile development area that communities in Southern California are familiar with is the old landfill, the old Shell Oil refinery, and surrounding areas in Carson City, California. This development area is environmentally impacted and was once being considered for a new National Football League (NFL) stadium and now will house the New Porsche Experience Center Los Angeles. Despite the loss of the NFL stadium plan, Carson City officials are negotiating with big name developers for commercial and residential developments at the impacted land. According to the city's director of community and economic development, "Systems to capture methane gas and prevent toxic substances from leaking into the groundwater and affecting nearby residences have been installed and are fully operational," (Long Beach Business Journal, 2016).

Additionally, geographic areas in California where ground water protection is eminent for supply of safe drinking water to the public have put special restrictions on how contractors and owners plan to and eventually support heavy structures. The Santa Clara County Water District (SCCWD) and the Alameda County Water District (ACWD), have developed special permitting mechanisms to protect groundwater from surface water infiltration and groundwater leakage. For example, in Fremont California, ground water protection is a major concern for the public where the ACWD will not allow foundations that penetrate the soil mantle above and below ground water zones, except in special mitigating circumstances (ACWD Ordinance 2010-01).

It is clear that Code changes, environmental regulation, and specific geographic regulations cause geotechnical and structural engineers to be thoughtful and careful in the selection of foundation support. The need for acceptable foundation solutions that are environmentally friendly, protect soil and ground water, and provide reliable, long-term foundation support is on the rise in California. Next, considerations for ground improvement and some of the recent ground improvement systems used in California will be discussed.

Foundations Supported on Improved Ground

Whether a site is just soft and compressible or environmentally impacted, the structural engineer may ask, "Can I get a higher bearing capacity? We can't drive piles because of the neighbors (due to noise and vibration concerns) and drilled concrete piers cost too much money. What other options are available?" The structural engineer may look to the geotechnical engineer and geo-contractors for a ground improvement method that increases the bearing capacity of the soil and controls foundation settlement, while being considerate of noise and vibration levels for neighboring residents. Geo-contractors will often recommend improving the soil with semi-rigid inclusions of compacted soil, sand, and gravel, or rigid inclusions of soil-cement, engineered grout, and concrete.

In California, discrete, semi-rigid and rigid inclusions are increasingly installed to improve bearing capacity and to reduce settlement in soft, loose, and compressible soil. The soft soil is improved by processes involving compaction, replacement, displacement, or on-site and in-ground mixing. The replacement process involves the removal of on-site soil, for example, from a drilled hole, and replacing the space with imported materials (such as sand, aggregate, or other select materials). The displacement process involves the use of powerful mechanical drills to displace deep soil laterally into the adjacent ground, causing compaction and increases in density and stiffness of adjacent soil using a drill displacement tool or mandrel (or similar tool) while generating little soil spoil.

The replacement, displacement, and mixing processes improve the ground by forming an inclusion-matrix of soil/inclusion composite cells or composite ground. The soil and inclusion composite cell is often called "composite ground." Replacement and displacement ground improvement is generally achieved by increasing the stiffness of soft soil with the remnant inclusion of stiffer materials. For the structural engineer, composite ground results in increased bearing capacity and control of settlement.

The load transfer mechanism of foundations supported on composite ground is different from a conventional pile foundation. Conventional pile foundations transfer the applied load to deeper bearing strata. The composite ground, on the other hand, distributes the structural loads both to the surrounding soil (now strengthened by the inclusion) and to the deeper soil zone below the composite ground. When choosing between a composite ground or conventional pile foundation, the structural engineers need to consider 1) constructability, 2) noise and vibration limits, 3) soil confinement in soft and liquefiable layers, 4) the presence of contamination, 5) adjacent structures and civil works, 6) settlement tolerance, and 7) the structural loads being supported.

For composite ground, settlements are usually calculated in two zones: the improved zone based on composite stiffness methods and the deeper zone (below the improved zone) using conventional geotechnical calculation methods (Majchrzak et al, 2004). Settlement calculation for composite ground consisting of rigid inclusions and disconnected piles is generally more involved than other types of inclusions, and can use a pseudo-pile analysis process (Siegel 2011).

General Description of Construction Methods

Modern ground improvement methods started with simple earthwork grading, often referred to as remove and recompact (or RnR) to replace soft soil with "engineered fill." When the depth of soft soil is impractical to RnR, then ground improvement systems forming composite ground can fill in the gap before a deep pile foundation is considered. Ground improvement comes in several forms and can be described by resulting stiffness and inclusion type. For example, aggregate piers can be considered a "semi-rigid" inclusion with low- to medium-stiffness. This section briefly describes current ground improvement processes used in California.

A. Sand inclusions (semi-rigid inclusions with low to medium stiffness). Often referred to as sand compaction piles, sand inclusions were first constructed between 1830 and 1850 in Japan. A technique to compact sand piles was developed in the early 20th century (USACE, 1987). Sand inclusions, generally 24 to 32 inches (and as large as 80 inches) in diameter, are usually constructed by vibro-driving a steel pipe mandrel, with a special end restriction, through layers of loose to firm soil, or very soft to firm silt or clay. Sometimes water jets are used to facilitate penetration through dense soil zones. During and immediately after driving, the pipe is filled with sand that exits at the bottom into the void left by the displaced soil. The sand and adjacent soil is then densified by vertical vibration and repeatedly raising the pipe 6 to 10 feet and vibrating it down 3 to 7 feet until it is withdrawn from the ground (USACE, 1987, 1999). A majority of sand compaction piles have been used in Japan and Taiwan to support stockpiles of heavy materials and various types of tanks and embankments. Depths of treatment can vary depending on equipment types and soil conditions, but generally range from 20 to 100 feet on land.

B. Aggregate inclusions (semi-rigid inclusions with low to medium stiffness). Aggregate inclusions are installed using one of three distinct procedures: vibrated displacement, vibrated replacement, and tamped replacement. It is important to note that vibrated methods can exhibit lower stiffness than tamped replacement methods, which highly depends on the soil conditions. The vibrated and tamped methods are discussed below.

1. Vibrated aggregate inclusion methods include: traditional vibrated stone columns and proprietary methods like Vibro piers® and Impact® pier. The primary target mechanism and result of vibrated aggregate inclusions is the densification of loose sand. The idea of stone column ground improvement dates back to the 1830s in Germany, but it did not receive acceptance in the United States until the 1970s (Griffith, 1991). Stone columns are typically installed in one of two ways, either by using an electric or hydraulic vibroflot hung from a crane, or using a vibrated pipe with a hydraulic piling vibrator from the top of the pipe, also known as vibro-rod.

   The vibroflot imparts horizontal vibrations into the ground at the depth where the vibroflot is located. The vibro-rod imparts vertical vibrations into the ground from the top of a pipe or probe mandrel where it is connected to the piling rig (Farrell et. al. 2010). Stone and aggregate can be fed from the top or from the bottom in dry or wet conditions. Wet bottom-feed methods use water jets to facilitate penetration. Aggregate is compacted by repeated re-insertion of the vibroflot or the vibro-rod. These installation methods can be used to install grout or cement-treated aggregate to achieve higher stiffness. The vibrator typically weighs on the order of 10,000 to 20,000 pounds and generates a centrifugal force of 43,000 to 70,000 pounds (Bauer Maschinen GmbH, 2012). Depths of treatment for a vibroflot typically vary from 15 to 100 feet. Depths of treatment for a vibro-rod typically vary from 15 to 45 feet.

2. Tamped and compacted aggregate inclusion methods include proprietary systems like Terrapier®, Georam®, and Rammed Aggregate Pier®. The primary target and result of tamped and rammed aggregate inclusions is the replacement of soft and compressible soil with a stiff, compacted, aggregate pier. In California, Caltrans and the Division of State Architect have referred to this method of construction as rammed aggregate columns and compacted aggregate piers, but they are commonly known as Geopier® or Rammed Aggregate Pier®.

   This replacement aggregate inclusion method is a recent invention developed by Dr. Nathaniel Fox in 1984. The invention was for soil reinforcement by installing a short, compacted, aggregate pier in a drilled hole with a beveled tamping foot, commonly referred to as "a tamper." The tamper is connected to small amplitude hydraulic break hammer that delivers a rated energy ranging from 250,000 to 1.7 million foot-pounds per minute, tamping at a frequency of 5 to 10 Hz (HITEC, 2007). The RAP is a replacement aggregate inclusion method where a soft soil is removed from a drilled hole, then replaced by aggregate that is compacted in 12- to 24-inch-thick lifts. Depths of treatment generally range from 10 to 25 feet where boreholes will remain open without collapse. The RAP method of construction includes off-haul or management of 100% of the replaced soft soil.

C. In-situ cement-mixed inclusions (rigid inclusions with medium to high stiffness). The mixing of soil with cementing products has been referred to as soil mixed columns, soil cement columns, deep mixing method (DMM), and deep soil mixing (DSM). Two types of DMMs are used in the United States: wet mixing and dry mixing. Wet mixing involves injecting binders in slurry form to blend with the soil. Primarily single-auger, multi-auger, or cutter-based mixing processes are used with cement-based slurries to create isolated elements, continuous walls or blocks (for large-scale foundation improvement), earth retaining systems, hydraulic barriers, and contaminant/fixation systems. Dry mixing uses binders in powder form that react with the water already present in the soil. Single-auger dry mixing processes are primarily used with lime and lime-cement mixtures to create isolated columns, panels, or blocks for soil stabilization as well as reinforcement of cohesive soils (FHWA, 2013).

Soil mixing was first developed in the United States in the 1950s as "intrusion grout mixed-in-place piles." It was utilized by the Swedes in the 1960s and 1970s for lime stabilization, and further refined by the Swedes and the Japanese in the 1970s and 1980s; then reintroduced back into the United States in the 1980s (Andromalos, Hegazy, and Jasperse, 2001). Applications of deep soil mixing have included hydraulic cut-off walls, excavation support walls, ground improvement foundation support, liquefaction mitigation, and environmental mitigation. Depths of treatment generally range from approximately 25 to 130 feet. The wet method of DMM can generate a considerable volume of spoil to be off-hauled or managed (FHWA, 2013).

D. Grout, sand-cement, and concrete inclusions (rigid inclusions with high to very high stiffness). Grout and concrete inclusions are constructed with drilled-replacement and drilled-displacement methods. These methods originate from piled raft foundations over soft and compressible soil. Ground improvements including this method of composite ground include Cast-in-place Ground Improvement Elements, Controlled Modulus Columns®, and Drill Displacement Column™ (DDC).

The DDC ground improvement method improves soft soil with 1) drill displacement compaction, followed by 2) pressure grouting during withdrawal of the displacement tool, and 3) leaving a remnant, undulated, grout column in the ground. The DDC is constructed with well-defined, uniform, low-permeability, engineered grout or concrete. Grout mix designs include stabilizer to control segregation of the mix. Grout uniformity is very important for strength and permeability. Typical constructed grout strengths range between 1,000 to 4,000 psi at 28 days. Typical permeability of Farrell's engineered mixes range from $1x10^{-7}$ to $1x10^{-9}$ cm/sec.

At the design depth, a bottom pressure bulb is developed in the bottom 2 to 5 feet with up to 10- to 15-bars of pressure in the pumped grout. The pressurized zone, just above the bottom bulb, is installed with pumped grout pressures in the 3- to 5-bar range. Withdrawal rate, grout pressure, and grout volume are measured and recorded electronically in real-time. The DDC composite ground capacity is verified with a full-scale load test and the DDC is sometimes fully instrumented for strain measurements. Limited soil cuttings are generated with the displacement auger which reduces the necessary handling and disposal of unwanted soil spoil.

Typical DDC nominal diameters are between 16 to 24 inches (pressure grouting often increases the effective diameter from 10 to 20%). Depth of penetration generally ranges from approximately 10 to 85 feet, although DDCs can be installed deeper. After the DDC has been installed, and the top of the column is built to the correct elevation, a load transfer platform or an aggregate cushion is placed to separate the composite ground from the foundation or embankment.

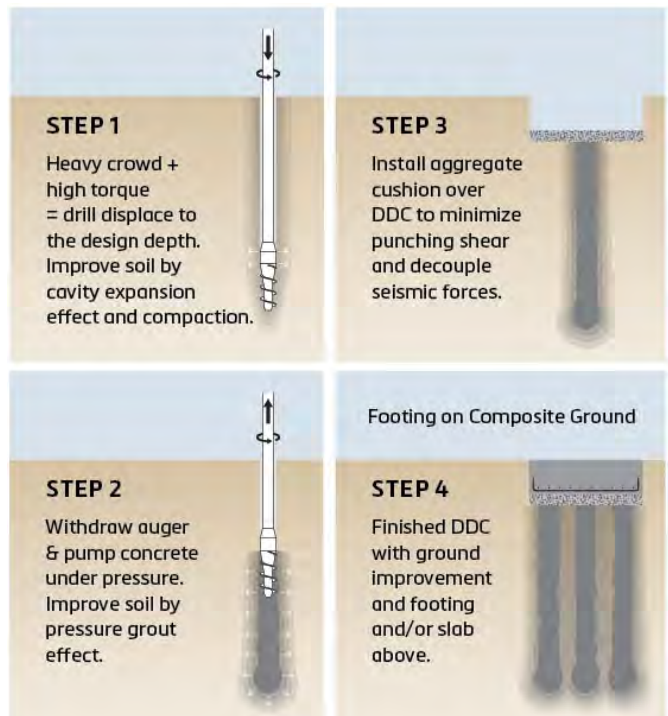

Figure 1: Drill Displacement Column™ (DDC) no-vibration, construction process to form composite ground.

For project sites with soft soil, heavy loads, landfill, contaminates, ground water protection requirements, and environmentally impacted soils, the DDC ground improvement method results in low-permeability, composite ground, that is desired by the regulatory agency to control the possibility of cross-contamination of water between aquifers or from surface water migrating deep into the soil profile.

Structural Considerations for Design

The various methods of inclusion-type ground improvement provide composite ground that the structural engineer can rely on for the support of heavy foundation loads. Key questions and considerations that the structural engineer needs to know about for the various ground improvement methods include:

1. What is the stiffness of the composite ground?
2. Will the composite ground shear or bulge under static and seismic loads?
3. Will composite ground behave uniformly or vary across the project site?
4. Does the composite ground need to be confined within liquefiable soil zones to provide reliable support?
5. Is the increased bearing capacity uniform under a conventional spread footing?
6. Does the composite ground reduce total and differential settlement to tolerable limits?
7. Is a structural slab between foundations required or can composite ground support a slab-on-grade?
8. Does the composite ground improve sliding friction and lateral resistance of the foundation?
9. Can the composite ground provide ground anchorage to resist overturning forces?

These questions are often answered by geotechnical engineers and specialty geo-contractor engineers in today's building industry in California. Each of the inclusion methods noted herein offer particular benefits and limitations. For example, benefits of composite ground include cost savings compared to deep pile foundations. With the DDC displacement and pressure grout method, composite ground will leave contaminated soil in place, and the engineered grout mix is left behind to plug and prevent cross-water contamination. Limitations to composite ground sometimes include the need to provide overall site densification or the need for additional confinement in liquefiable soil layers at a reasonable cost.

Advances in California – DDC Case Histories

Engineers at Farrell Design-Build worked on the first project in California that was supported by Rammed Aggregate Pier®, the South Napa Marketplace in 1995 (Blackburn and Farrell, 1998). Case histories of RAP systems in California are present in the literature with detailed discussions of RAP design, uplift testing, liquefaction reduction, and settlement monitoring results that are also documented in the literature (Majchrzak et al, 2004, Farrell et al, 2008, Fiegel and Farrell 2008). Farrell has been successful with obtaining approval for RAPs at UC, CSU, BART, DSA, Caltrans, and several cities and counties in California.

Some of the regular challenges with RAP construction in California include the proprietary system not being well accepted by public agencies for public bidding, vibration sensitive projects, and contaminated sites. Vibro piers® and RAP aggregate pier systems are normally considered permeable, as a result environmentally impacted sites are usually not feasible.

City of Berkeley Animal Shelter, Berkeley, CA. Farrell introduced the Drill Displacement Column™ system to California in 2010 with the first commercially installed DDC at the City of Berkeley's new Animal Shelter. The site was subject to strict vibration monitoring because of the East Bay Mud 66-inch sanitary sewer interceptor pipeline within 5 feet of the eastern property boundary. The project site had contaminated soil, soft bay mud, and liquefaction hazards that required ground improvement to support the mat foundation. Farrell was awarded the project with a grout-treated RAP system, but the vibrations caused problems. Farrell started the RAP construction, but it was halted due to the excessive vibrations at the beginning of construction 50 feet away from the 66-inch sewer. "As a result of the vibration tests, the piers had to be redesigned and the method of installation changed," according to city staff (Raguso, 2013). Farrell engineers redesigned the foundation support system to use the non-vibratory DDC. The project was completed with DDC and the sewer pipe was inspected with no new cracks, it was a success for the City of Berkeley and Farrell.

Since this first project, many projects have used the DDC system and its ground improvement benefits to support heavy loads, reduce liquefaction potential, and manage ground water protection, and contaminated soil concerns. The following four notable DDC case histories show where the system was used in California to overcome seismic and environmental challenges. To meet the Code changes and regulatory requirements, DDCs are increasingly being recommended by geotechnical engineers as a ground improvement system to increase bearing capacity and reduce settlement below heavy structures. DDCs have performed well during earthquake loading as exhibited by the 2014 Napa earthquake, described in the California Maritime Academy case history below.

California Maritime Academy – Dining Center, Vallejo, CA. The California State University (CSU) – Cal Maritime Academy in Vallejo planned the construction of a new dining center at the campus. The project consists of a 3-story, steel moment frame structure with a south-facing, glass wall overlooking San Pablo Bay. The structure location is just 80 feet from the bay's edge. Undocumented fill, contaminated fill, colluvium rock, loose sand, and bay mud were discovered beneath the site during geotechnical investigations. Sloping bedrock toward the bay added to the potential geologic hazards with lateral spread concerns for the new structure and improvements. The CSU Regents and the design-build general contractor selected Farrell Design-Build and the DDC system as the appropriate method to mitigate static settlement, liquefaction-related settlement, and lateral spread hazards. The CSU peer reviewer and Geotechnical Engineer approved the numerical analysis performed by Farrell engineers using the DDC method of composite ground reinforcement. Farrell installed more than 500, 18-inch diameter DDCs at the site to depths of 38 feet. In October of 2013, the dining center structure was complete and the dining center was in service.

About one year later, on the morning of August 24, 2014, the Napa earthquake (M_w = 6.0) was felt 100 miles from the epicenter. The dining center site sits about 11 miles south of the epicenter. Approximately 1.2 miles south of the dining center, two seismic stations measured the PGA at the Carquinez Bridge abutments with values of 0.34g and 0.7g with acceleration spikes nearly 1.0g recorded in the Geotechnical Array No. 1 in the north-south direction (GEER 2014). After the earthquake, Farrell staff performed a site review and an interview with the campus facilities manager to assess the structure's performance. Mr. Bob Brown, facilities manager at Cal Maritime noted that, "…we felt it shaking quite a bit, but the only damage at the dining center was a few plates and glasses knocked over onto the floor." Visual inspections showed no ground cracks or signs of lateral spread at the DDC buttress, which was effective at holding back the liquefiable soil and the structure.

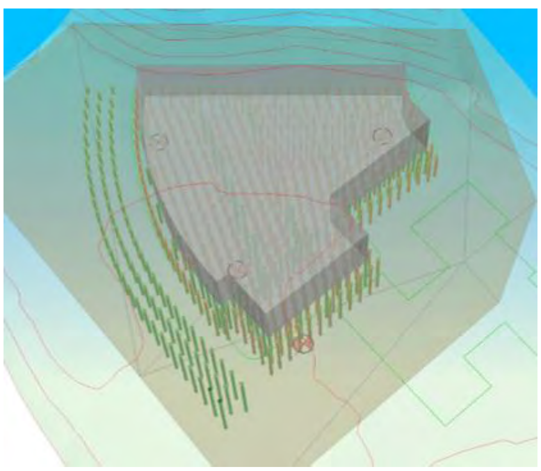

Figure 2: Visualization of DDC Ground Improvement at California Maritime Academy Dining Center.

Maxwell Field Parking Structure, UC Berkeley. The University of California at Berkeley planned to replace the old practice field just north of Memorial Stadium with a new two-story parking structure and a new practice field on the roof. The site is situated just 75 feet south and west of the Hayward fault. In addition, the site rests over a canyon fill on the historic Strawberry Creek. Since the 1930s, the Little Inch box culvert has been the main drainage channel for Strawberry Creek and sites between 20 to 34 feet below the ground surface directly under this site. The main geologic hazards for the site were seismic settlement, static settlement, and foundation support for the new garage, and to protect the still active Little Inch box culvert.

The DDC solution was selected for foundation support for the following reasons: 1) the DDC system is a displacement method that will compact soil laterally thus reducing seismic settlement between and around each DDC, 2) the DDC installation is drilled with no vibrations, thus protecting Little Inch during the construction, and 3) the engineered grout mix acts as a plug to prevent cross-contamination between the contaminated soil above and the groundwater below.

The challenge for the structural engineer and the design team was to creatively position structural columns and footings to straddle the Little Inch and Big Inch culverts. The sloping bedrock profile with a survey of Little Inch was modeled by Farrell and presented to the structural engineer and design team with proposed DDC locations around Little Inch, see Figure 3. Over 480, 18-inch-diameter DDCs were installed between depths of 8 to 40 feet below the ground surface. Load test results and post-installation CPT and DMT tests showed acceptable performance of the DDC system and the soil that was compacted within two diameters around the DDCs.

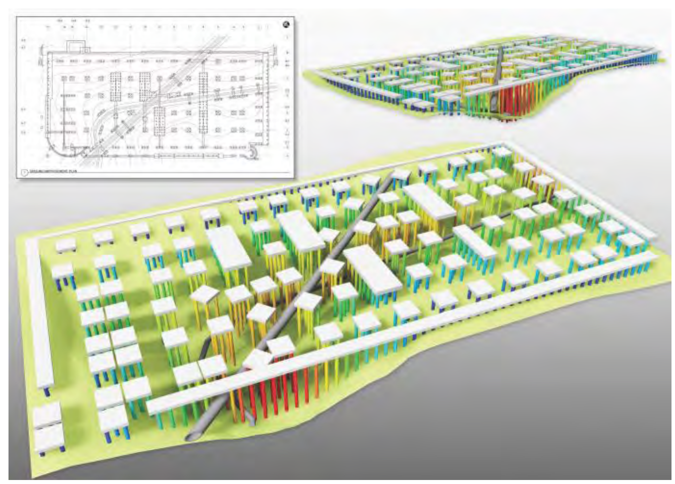

Figure 3: Visualization of DDCs, sloping bearing stratum, and existing culverts at Maxwell Field Parking Structure.

Bay Area Rapid Transit and Valley Transportation Authority - San Jose Extension, Milpitas Station, CA. DDC ground improvement was selected to support the new 6-level parking garage as part of the Bay Area Rapid Transit (BART) San Jose Extension. This federally funded project was performed under considerable peer review by BART and Valley Transportation Authority (VTA). The Milpitas site was part of single story storage facility that had high levels of lead contamination in the soil (Langan, 2015). The site also had high levels of other contaminates in the ground that required special handling and minimal disturbance. Structure column loads varied from 250 kips to 1,800 kips.

The site is underlain by alluvial deposits that consist of soft to medium stiff clay to 26 feet and then over-consolidated clay and various sand and gravel to depths of 80 feet. Langan recommended ground improvement inclusions forming composite ground including RAP and DDC. The contractor selected the use of DDC the system to support the new construction because 1) the high stiffness of DDC in the soft clay soil and 2) the resulting impermeable grout plug left behind in the soil profile that blocks near-surface contamination from penetrating to lower soil and groundwater zones, and 3) nearly eliminated contaminated soil off-haul. DDC ground improvement formed composite ground with an improved bearing capacity of 7,000 psf. Farrell installed over 550, 18-inch diameter DDCs to depths of 30 feet with 40-hour HAZWOPER crews. At the end of construction, DDC equipment was decontaminated, so that any hazardous soil was left at the site.

Figure 4: BART/VTA Milpitas Station Parking Structure vertical construction nearly complete.

237 at First, San Jose, CA. South Bay Development had planned development on the site since 2007. Two 6-story moment frame, class A offices were planned for the site. The work was subject to the Local Enforcement Agency Review due to the site constraints being a closed landfill and ground water protection.

The project environmental engineers had to obtain approval for construction on the site from the San Francisco Regional Water Quality Control Board (RWQCB). Farrell provided previous project data for sites with ground water protection requirements that included the engineered mix design of grout and Controlled Low Strength Material (CLSM) with permeability tests of the production grout mixes. The RWQCB approved the use of Drill Displacement Column™ ground improvement for foundation support of the project through the landfill, citing the "Suitability of DDC Methodology for Contaminated Sites," (RWCQB, 2014).

The geologic hazards for the project included the landfill, the soft clay immediately beneath the landfill, and the liquefiable sand zones beneath the clay. The DDC system formed composite ground with an improved bearing capacity of 6,000 psf for support of shallow footings. DDCs supported the slab and footings in addition to mitigating liquefaction settlements below foundations to less than 3/4-inches. Farrell installed over 1,000 DDCs per structure, to depths of 50 feet with a diameter of 18 inches. Grout permeability was tested to exhibit 1×10^{-9} cm/second, well below the RWQCB requirement. Load test results and post-installation CPT and DMT tests showed acceptable performance of the DDC system and the soil that was improved and compacted around and between the DDCs.

Conclusions

As more earthquake data is recorded and structural performance during earthquakes is evaluated, the industry will continue to adjust with Code changes. As the Code continues to evolve with respect to requirements for building construction/performance, the foundations that support these structures will also change. California's building industry has been undergoing a considerable upgrade since the 1971 San Fernando Valley earthquake with several legislations that define and control building design and engineering. With new land becoming less available, developers and public agencies are using environmentally challenge land for building construction. Both cases, have led to an emergence of ground improvement systems that form composite ground for structural support.

The recent uses of semi-rigid, aggregate inclusions and rigid, grout inclusions, such as DDCs in California, has given rise to advances in ground improvement to support heavy foundation loads. The introduction of the RAP system in 1995 led to mainstream ground improvement foundation support in California. And recently, the Drill Displacement Column™ system has provided geotechnical and structural engineers with a reliable foundation support system that forms composite ground with sensitive environmental benefits. Particularly, the recent successful performance of DDCs during the 2014 Napa earthquake gives structural engineers a level of confidence to recommend and use ground improvement forming stiff composite ground – for foundation support. The DDC system has been approved by UC, CSU, BART, PGE, ACWD, SCCWD, RWQCB, and several cities and counties in California at landfill and environmentally impacted sites.

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