Deep dynamic compaction for subgrade improvements within the Port of Long Beach, California

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The Port of Long Beach in Southern California decided to construct a new maintenance facility as a part of a 70,000 square-meter land development project. Figure 1 shows location of the project site. The facility includes a two-story structure with a footprint area of approximately 5,300 square-meters and is located less than 800 m southwest from downtown Long Beach.

Prior to construction, geotechnical uncertainties emerged in this seismically active environment. It was confirmed that the site was reclaimed in the early 1950's from the Pacific Ocean and filled with dredged, potentially compressible and liquefiable materials mostly mixtures of silt and sand, up to 16.5 m thick. In addition, rock slope protection/ construction debris (rubble) were known to be present within the fill and, as shown in Fig. 1, were identified to bisect the project site in southwest-northeast direction. Considering challenges presented by the buried rock and rubble fill, remedial option were developed to mitigate the impacts of soil liquefaction and seismic-induced settlement estimated on the order of up to 150 mm during a major seismic event. Remedial options to improve on-site soils included stone columns, driven steel H-piles, reinforced soil mat, and deep dy-

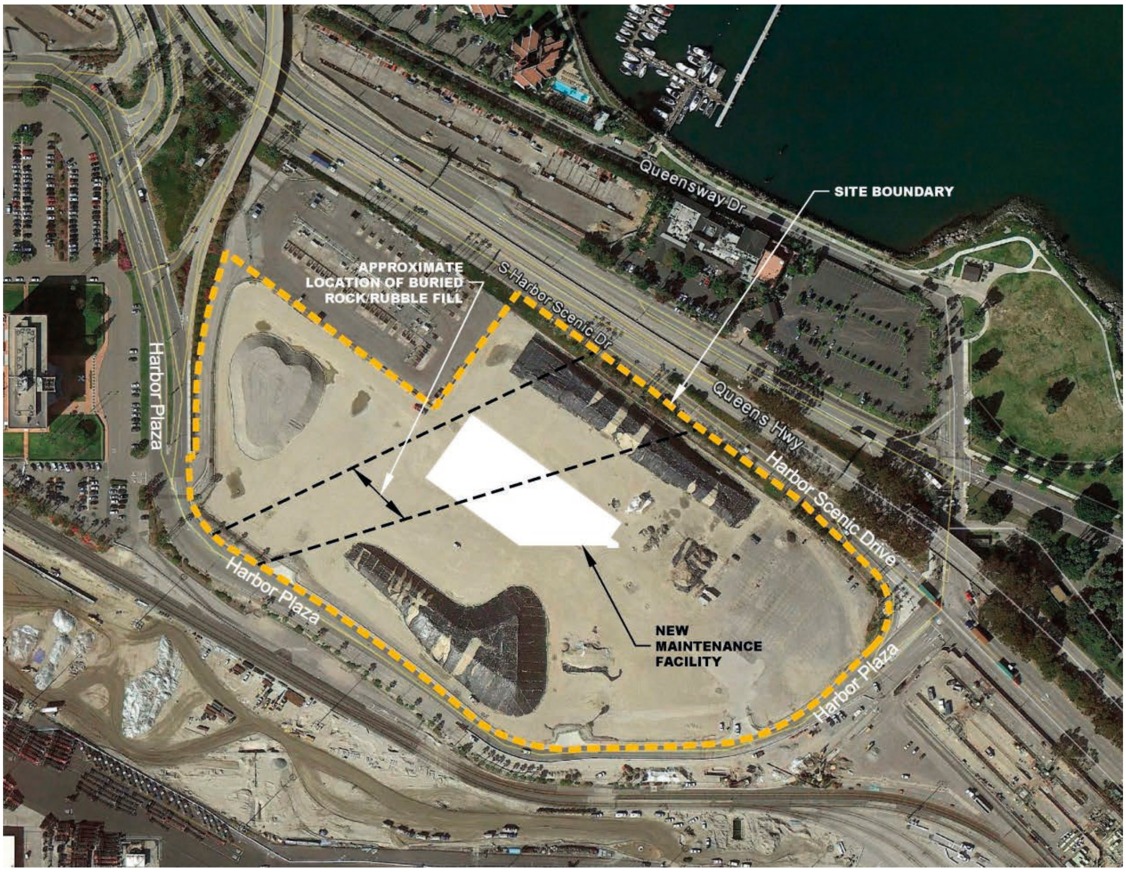

Fig. 1. Site for New Maintenance Facility at the Port of Long Beach

namic compaction (DDC). The use of vibro-displacement stone columns or driven piles was questionable and even impractical due to the presence of the rock/rubble fill up to approximately 12 m deep and a potential for very difficult penetration of this material. A reinforced soil mat would not be expected to eliminate the potential for liquefaction-induced settlement and reduce it to a magnitude acceptable from the structural standpoint. After careful examination of each remedial measure, a DDC solution was selected as an affordable and sustainable ground improvement method, proven for densification of granular soils, particularly non-homogenous rubble fills [1, 2].

The DDC process applies repeated impact of heavy weights, to compact zones of loose fills. This process is simple, fast, and cost-effective. While DDC ground improvement has been used in numerous projects in the U.S. since 1978 including the Port of Long Beach, the maintenance facility location posed some unique challenges. The site is close to existing structures and active underground oil lines. The Port of Long Beach and the design team were concerned that ground vibrations from DDC activities could impact and potentially damage the nearby building structures, pipelines, as well as be disturbing to people.

SUBSURFACE SOIL CONDITIONS

The subsurface stratigraphy and geotechnical engineering properties at the project site were evaluated based on an extensive exploration program and laboratory data. The principal soil deposits consisted of man-made fill underlain by natural deposits. The fill generally consists of alternating layers of very loose to medium dense sands and occasionally very soft to medium stiff clays. The thickness of fill observed in exploratory borings ranged from approximately 13 m to 16.5 m. The natural deposits generally consisted of very soft clays and silts (harbor bottom deposits) underlain by medium dense to very dense sands and occasionally very stiff clays.

A construction rubble fill, up to approximately 12 m thick encountered in the central portion of the project site, crossing the site in southwest to northeast direction, consisted of a mixture of sandy soils with a large amount of concrete debris, up to 1.8 m in size. A photograph showing construction rubble fill encountered within one of exploratory test pits is shown in Fig. 2.

Fig. 2. Construction Rubble Fill

DDC PILOT TEST PROGRAM

Prior to implementation of the full-scale DDC across the entire footprint area of the proposed structure, a pilot test program was implemented to evaluate the effectiveness of this ground improvement technique and establish recommended criteria for this project such as spacing of impact points, applied energy, and phasing. Concurrently, a system was installed to continuously monitor the project site and nearby structures to evaluate vibration impacts to nearby improvements. A DDC pilot test area of approximately 15 by 15 m was selected within the future building pad area and subjected to high-energy impacts performed in three phases by repeatedly lifting and dropping a 27.2 Mg tamper from a height of 24.4 m. The spacing of tamping points was approximately 2.3 m in a square arrangement, and the number of drops per each location ranged between 4 and 10. An average energy application of nearly 10.1 MJ/m^2 was applied over the pilot test area. The DDC equipment including a 118 Mg crawler crane and a 27.2 Mg tamper are shown in Fig. 3 and 4. The layout of pilot test program with the DDC multiple passes is shown in Fig. 5.

Selection of tamper weight, drop height, grid spacing, multiple passes, and applied energy were evaluated and pre-selected based on the results from the subsurface exploration program and the desired depth of densification to satisfy design requirements.

Field monitoring included measurements of ground vibration at different distances from the tamping point, depths of crater formation following each series of drops, average ground loss, and ground heave (if any) at selected locations during the densification process. Craters up to 2 meters deep and up to nearly 5 meters in diameter were observed at tamping locations following primary drops as shown in Fig. 6.

To evaluate the effectiveness of ground improvement and to estimate anticipated total and differential seismic-induced settlement, series of cone penetrometer tests (CPTs) were performed within the DDC pilot test area before and after DDC. Collected results indicated significant ground improvement within the upper 10 meters, resulting in reduction of seismically-induced settlement, as shown in Fig. 7, from approximately 150 mm prior DDC to approximately 50 mm following completion of DDC. Based on the obtained data, an average uncorrected CPT tip resistance of at least 11.5 MPa over an effective interval of 1.5 meters to the depth of 10 meters was selected as the performance-based criteria required for this project.

Fig. 3. Crawler Crane and Tamper

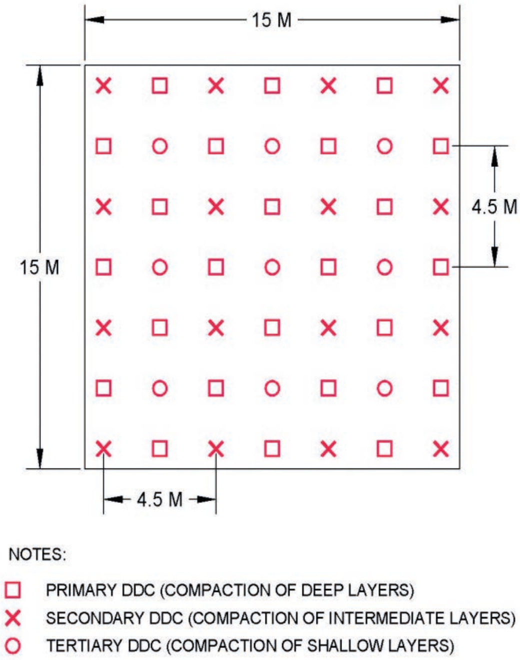

Fig. 5. Pilot Test Program Layout with Multiple Passes

Fig. 4. Tamper

Fig. 6. Crater at Tamping Point

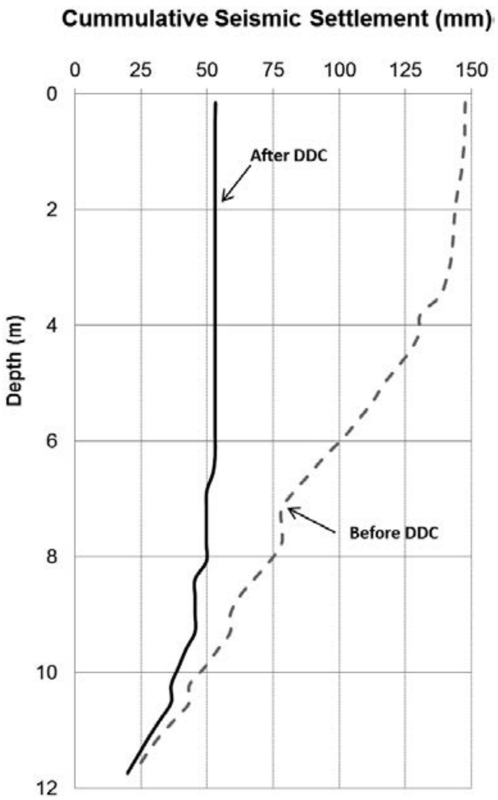

Fig. 7. Estimated Seismically-Induced Settlement

Comprehensive ground vibration monitoring was performed during pilot test program to assess the relationship between the induced ground vibration, the applied energy, and the attenuation of ground vibration with a distance. Fig. 8 shows the monitored vertical, longitudinal and transverse peak ground velocities (PGV) at various distances from the impact point. Generally, PGV above 50 mm/sec is considered to cause potential damage to the nearby structures.

Due to the lack of data regarding the conditions of the existing oil pipelines and presence of relatively old structures in the immediate vicinity of the project site, a maximum PGV less than 12.5 mm/sec was selected as a recommended criteria resulting in a required minimum safe distance of 40 m between the impact point and adjacent structures. Since the existing pipelines and some other on site improvements are as close as 30 m from the perimeter of the building pad, mitigation measures to reduce impacts to the existing improvements needed be considered and implemented during the full scale DDC operation.

FULL SCALE DDC

The full DDC operation within the future building pad area was performed in two phases. The first phase, dubbed "high-energy" was designed to achieve the required densification criteria utilizing the same equipment and procedure as completed during the pilot test program described above. The second phase, dubbed "ironing", smoothed the ground surface for future site grading. A 13.6 Mg tamper with a drop of 12.2 m was utilized for the ironing phase. The average energy applied on a grid system across the pad area during the high energy and ironing phases were over 9.8 MJ/m^2 and 0.98 MJ/m^2, respectively.

To reduce the potential impacts to the existing oil lines and other nearby improvements, a temporary isolation open trench to prevent vibration transmission through the ground, approximately 3.6 m deep and 3 m wide, was constructed along the northwest project boundary as shown in Fig. 9.

Several velocity sensors, as shown in Fig. 10, were installed across the site and near the existing structures to record PGVs. Based on the collected vibration data, the trench was effective, reducing vibration levels by as much as 40 percent. Records from the nearly continuous monitoring show that vibration levels were at all times within recommended limits at and beyond the property line of the maintenance building site. As a part of quality assurance testing, series of CPT soundings were performed at selected random locations across the project site to confirm/verify densification criteria within the improved site.

Fig. 11 shows an example of uncorrected tip resistances measured in one CPT sounding prior to and following completion of DDC.

In general, post-DDC uncorrected tip resistances over an effective interval of 1.5 m to the depth of at least 10 m met or exceeded the specified minimum value of 11.5 MPa established as the performance-based criteria based on the results from the DDC pilot test program.

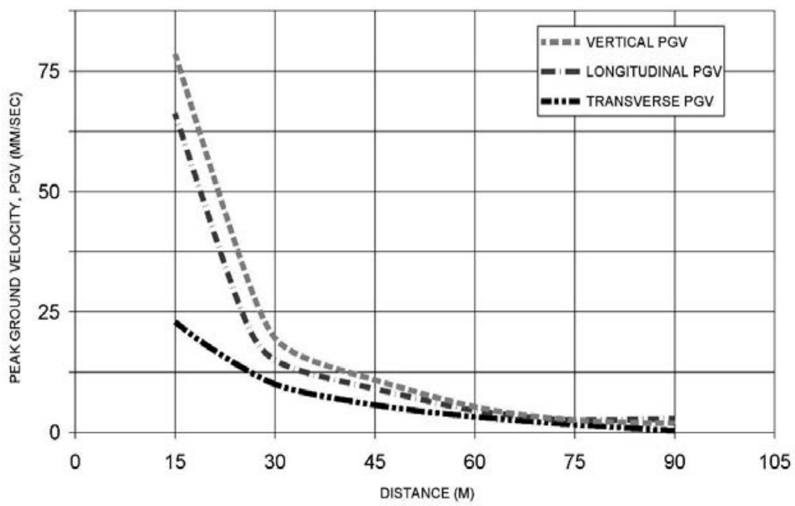

Fig. 8. Ground Vibration (PGV) versus Distance

Fig. 9. Temporary Isolation Trench

Fig. 10. Portable Vibration Monitoring System

CONCLUSIONS

Through the careful examination of potential mitigation measures to reduce seismic-induced settlement and based on site-specific conditions, the DDC technique was selected to improve subgrade conditions and was verified as a prudent an efficient, cost-saving and sustainable construction method for the subject site. Detailed analyses including comprehensive geotechnical investigation, modelling of anticipated geologic/geotechnical hazards, and the DDC pilot test program were the basis for development of specific recommendations, measures, and

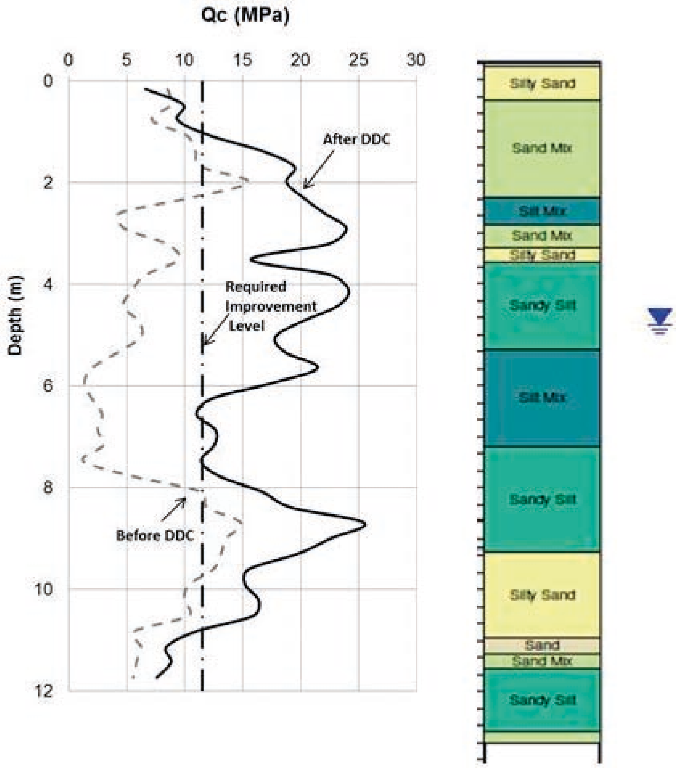

Fig. 11. Uncorrected CPT Tip Resistances

performance criteria during the construction phase of this project. It was verified by series of in-situ testing and observation that high energy waves created by the repeated impact of heavy weights can efficiently increase density of on-site hydraulic fills, increase bearing capacity, and reduce the potential for excessive seismically-induced settlement at the project site located in the highly seismic Southern California region.

REFERENCES

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2. Sieradzki M.: Deep Dynamic Compaction: Practical and Cost-Effective Ground Improvement at the Port of Long Beach, presentation at Ports 2013 ASCE Conference, Seattle, 2013.