MILLPORT SLOUGH BRIDGE: A COASTAL BRIDGE INCORPORATING LIQUEFACTION MITIGATION

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ABSTRACT

The design and construction of the Millport Slough Bridge located in the middle of the Siletz Bay Estuary along Oregon's Pacific coast required addressing the marine, seismic and environmental challenges of the site. This project provides a four-span, prestressed concrete girder bridge to replace the existing eight-span timber structure. It also addresses the liquefiable soils inherent to this location in an environmentally responsible manner. Precast-prestressed concrete pile were used in the construction of a liquefaction mitigation system at each abutment and incorporated into the seismic design of the bridge. This paper discusses the Millport Slough project's background and the unique solution developed by the design team.

Keywords: Liquefaction Mitigation, Shear Pile, PCPS Concrete Pile, Wick Drains

INTRODUCTION

The Oregon Department of Transportation is replacing a deteriorating and structurally deficient timber bridge that carries the Oregon Coast Highway (US101) over Millport Slough two miles south of Lincoln City, OR. The existing bridge was an eight-span, timber bridge with a concrete deck and supported by timber piles. The timber piles had deteriorated substantially and drove the need for the bridge replacement. Additionally, the existing horizontal clearances and safety features were substandard.

Surrounded by the Siletz Bay National Wildlife Refuge, environmental issues played a significant role in the direction and scope of the project. The bridge is adjacent to tidally influenced salt marsh, tidal sloughs and mudflats. This sensitive location provides habitat to eel grass, various species of waterfowl, shellfish (predominately soft-shell clams) and nursery grounds for chinook salmon, steelhead and cutthroat trout. The existing hydraulic opening was a constriction to Millport Slough and also a fish passage barrier during low tide events.

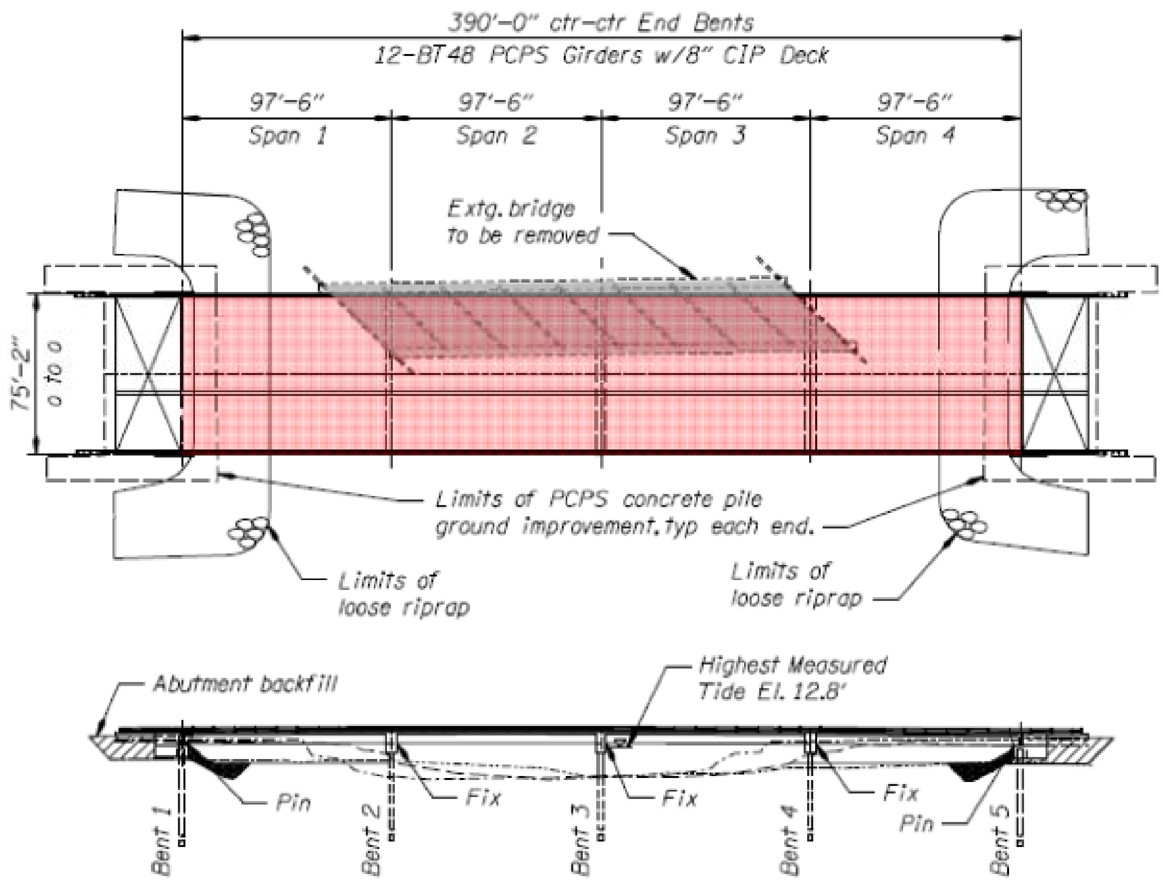

Fig. 1 – Plan and Elevation View of the Millport Slough Bridge

SUPERSTRUCTURE DESCRIPTION

A four-span, 390 foot long precast, prestressed girder bridge was designed for the site (see Figure 1). The roadway profile was raised to accommodate a deeper superstructure (48” Bulb-T w/ 8” thick deck) and reduce the number of bents.

SUBSTRUCTURE DESCRIPTION

The substructure consists of ten steel pipe piles at each bent supporting a reinforced concrete crossbeam. The interior bents are fixed to the superstructure and supported by PP24x0.75 pipe pile. The end bents are pinned to the superstructure and supported by PP30x0.875 pipe pile.

SITE GEOLOGY

The tidal mudflat geology of the side consists of deep (approximately 180-200 ft), relatively soft, sediments deposited in the Siletz Bay estuary, that is underlain by siltstone or sandstone. The estuary deposits consist of soft to medium stiff clay, clayey silt, silty clay, sand, sandy silts and very loose to medium dense silty sand. The geotechnical borings disclosed very loose to loose fine-grained silty sand with uncorrected Standard Penetration Test N-values ranging from 3 to 7 blows per foot in the upper 60 ft of sediments. The embankment height averages 18 feet at the bridge abutments. Earthquake-induced peak bedrock accelerations are estimated at 0.23 and 0.39 g for 500- and 1,000-year return interval seismic events, respectively.

LIQUEFACTION AND LATERAL SPREADING

Seismically induced liquefaction to a depth of 60 ft below the embankment fill is anticipated. Post-liquefaction settlements of up to 11 inches in the saturated, non-plastic alluvial silts and sands were estimated for the 500- and 1,000-year return interval seismic events.

Lateral spreading of the approach embankments is anticipated as a result of liquefaction. Lateral spreading involves the horizontal displacement of large volumes of soil as a result of the liquefaction of the underlying layers. The ground displacement occurs in response to the combination of gravitational and inertial forces generated by an earthquake and acting upon the soil mass. Lateral spreading develops on slopes and moves toward a free face, such as a river channel. Horizontal displacement may range from a few inches to many feet depending on soil conditions, the steepness and height of the slope and the magnitude and focal distance of the earthquake. A graphic example of the effects of lateral spreading on a bridge is shown in Figure 2.

Fig. 2 –Effect of Lateral Spread Loads on the Yuehe Bridge from 1976 Tangshan Earthquake (M7.8), China [Photo: Xu Fengyun]

Liquefaction mitigation measures were incorporated into the project based on the requirements of the Oregon DOT Bridge Design and Drafting Manual(1) that are intended to address lateral deformation of bridge approach embankments adjacent bridge abutments. Under these criteria, the bridge is designed to remain accessible to emergency vehicles after the 500 yr. seismic event and designed to avoid collapse of the bridge as a result of the 1000-year event.

The potential for lateral spreading was evaluated using soil strength properties for the liquefied embankment and underlying sediments. The undrained residual shear strengths were estimated from the CPT and Standard Penetration Test (SPT) data. Using residual shear strengths ranging from 200 to 400 psf in slope stability modeling, the approach embankments have a global factor of safety less than 1.0 for liquefied conditions without applying seismic lateral forces to the soil mass. The methods presented by Bray and Travasarou (2007)(2) were also used to estimate liquefaction-induced embankment deformations assuming a factor of safety slightly greater than 1.0. These studies indicate lateral movement on the order of 5 and 8 ft at the crest of the embankment slope for the 500- and 1,000-year return interval seismic events, respectively. The associated vertical displacements will be on the order of several feet and would likely include near-vertical scarps.

LIQUEFACTION AND LATERAL SPREAD MITIGATION

As demonstrated through numerous prior studies and projects, the risk of liquefaction and the associated slope deformations can be significantly reduced by completing ground improvement. Vibro-replacement stone columns are frequently the most effective and economical way to mitigate liquefaction and subsequent lateral spreading at the bridge approaches and abutments in similar site conditions. However, due to site conditions and environmental objectives of the project, stone column installation would require a steel sheet pile isolation system to control the extent of turbidity caused by compressed air returning to the ground surface. Such an isolation system would significantly increase the cost of stone column installation. Cement deep soil mixing (CDSM) methods were evaluated but were considered unacceptable from an environmental perspective due to the close proximity of the roadway fill to the estuary. Isolating the work area for these liquefaction mitigation techniques from the surrounding estuary was considered impractical or was estimated to cost more than the lateral spreading mitigation technique which was ultimately selected.

Due to the cost and environmental considerations of the methods described above, an alternative method for lateral spreading mitigation using shear piles was evaluated. This method uses vertical driven pile to stabilize slopes by embedding the bottom portion of the pile deep enough to develop fixity in the underlying soil and extending the top of the pile above the slope failure surface, as shown in Figure 3. Resistance to shear at the slope failure surface is developed through pile-soil interaction.

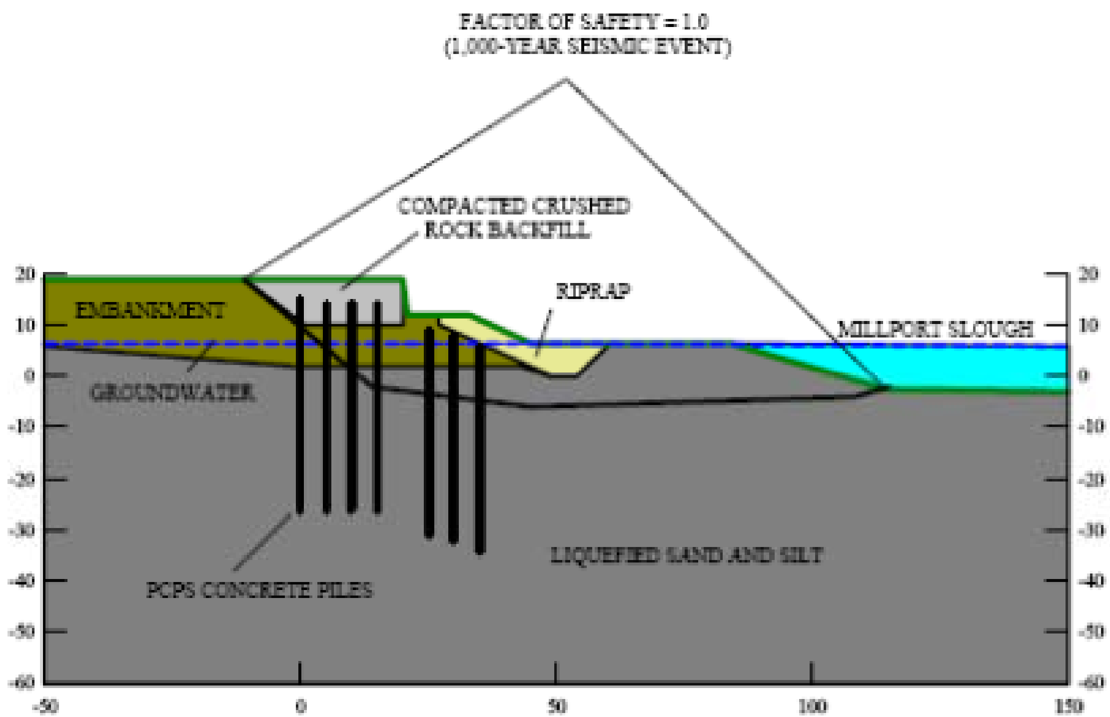

Fig. 3 – Slope Stability Model (Abutment to Slough)

Various pile types were considered for the shear piles. Treated timber pile was eliminated from consideration because of the relative low strength timber pile, leaching of preservative treatment into the sensitive estuary environment is not acceptable and the resulting footprint which would have extended into the slough at each bent. Steel piles were eliminated from consideration given the relative cost of the steel pile to concrete pile and corrosion potential in the marine environment. Additionally, the potential for decay or corrosion in the upper portions of the pile would limit the functional life of the timber or steel pile as the top of pile is periodically in unsaturated soil above the anaerobic zone.

Precast, prestressed concrete pile was selected for lateral spreading mitigation based on consideration of corrosion resistance, stiffness and cost. Several alternatives were considered for evaluating the lateral resistance of the concrete piles for use within the slope stability model. The selected methodology for design used the computer software L-Pile Plus v5.0 by Ensoft, Inc. of Austin, Texas to evaluate the lateral resistance of a single pile subjected to lateral soil movement on the upper portion of the pile. The resulting lateral resistance of the piles was compared to the simplified Broms (1964) [(3)] approach to evaluating the lateral capacity of a single pile. The soil conditions surrounding the pile were conservatively evaluated by assuming it is embedded in fully liquefied soil with an undrained residual shear strength of 250 psf. The additional shear resistance for slope stability provided by the pile was taken as the minimum of the following: 1) the pile shear strength, 2) the lateral resistance limited by the liquefied soil strength for the portion of the pile above the failure surface, or 3) the flexural strength of the pile to resist lateral loads imposed by liquefied soil (item 2) above the slope failure surface. The results indicate that for the soil conditions at this site, the nominal flexural strength of the concrete piles with 1 ft^2 cross section typically limits the effective lateral resistance of slope movement to about 9 ft deep. Improvements in lateral resistance to slope instability will be limited by the flexural strength of the pile even if higher strength soils are present.

The Bray and Travasarou (2007) approach was used to estimate embankment deformations following PCPS concrete pile installation for the 500- and 1,000-year return interval seismic event levels. This method uses an empirical database of slope displacement case histories to expand upon the yield coefficient methodology incorporated in the Newmark sliding block methodology. Estimated soil displacements are a function of the assumed earthquake magnitude, slope yield coefficient, the fundamental period of the slope, and the ground motions spectra acceleration at 1.5 times the initial fundamental period of the slope. The yield acceleration for an assumed critical slip circle is determined by incrementally increasing the horizontal acceleration in a pseudostatic slope stability analysis using SLOPE/W by GeoSlope International of Calgary, Canada or an equivalent slope stability evaluation method until a factor of safety of 1.0 is reached. Acceptable yield accelerations were back-calculated to limit median displacements to the acceptable values discussed in the ODOT Geotechnical Design Manual[(5)]. The acceptable yield acceleration was determined by assuming the calculated median slope displacement of 6 in. was acceptable at the 500-year hazard level. The following parameters were used to establish a yield acceleration of 0.12 g: M_{w} = 8.3, T_s = 0.27 s, S_a(1.5s) = 0.48 g. The number and layout of PCPS concrete piles was then adjusted to maintain a yield acceleration of 0.12 g in slope stability analyses using SLOPE/W. For a 1,000-year hazard level event assuming the following: M_{w} = 8.5, T_s = 0.27 s, S_a(1.5s) = 0.68 g., median displacements of 12 in. were estimated by applying the Bray and Travasarou methodology to the slope configuration with PCPS concrete piles.

The Contractor was required to submit a PCPS concrete pile design conforming to the AASHTO LRFD Bridge Design Specifications and the following performance specifications: minimum cross-sectional dimension of 12 inches, a minimum concrete cover of 3 inches, a nominal flexural capacity of 70 kip-ft and a nominal shear capacity of 25 kips.

The lateral spreading hazard was mitigated at both abutments using a total of 638 precast, prestressed concrete piles. The arrangement of piles for the south abutment, Bent 5, is shown in Figure 4. Piles were driven into the ground in a grid with four foot on-center spacing and pile lengths of fifty and sixty feet, depending on the location and need. The piles that surround the abutment (shown using a solid square symbol in Figure 4) are designed to provide resistance to lateral spread of the embankment. The additional shear piles under the bridge end panel (shown as a hollow square symbol in Figure 4) have a dual purpose. They provide resistance to lateral spread of the embankment (along with the other pile) and have been incorporated into the seismic design of the bridge as an Earthquake-Resisting Element (ERE).

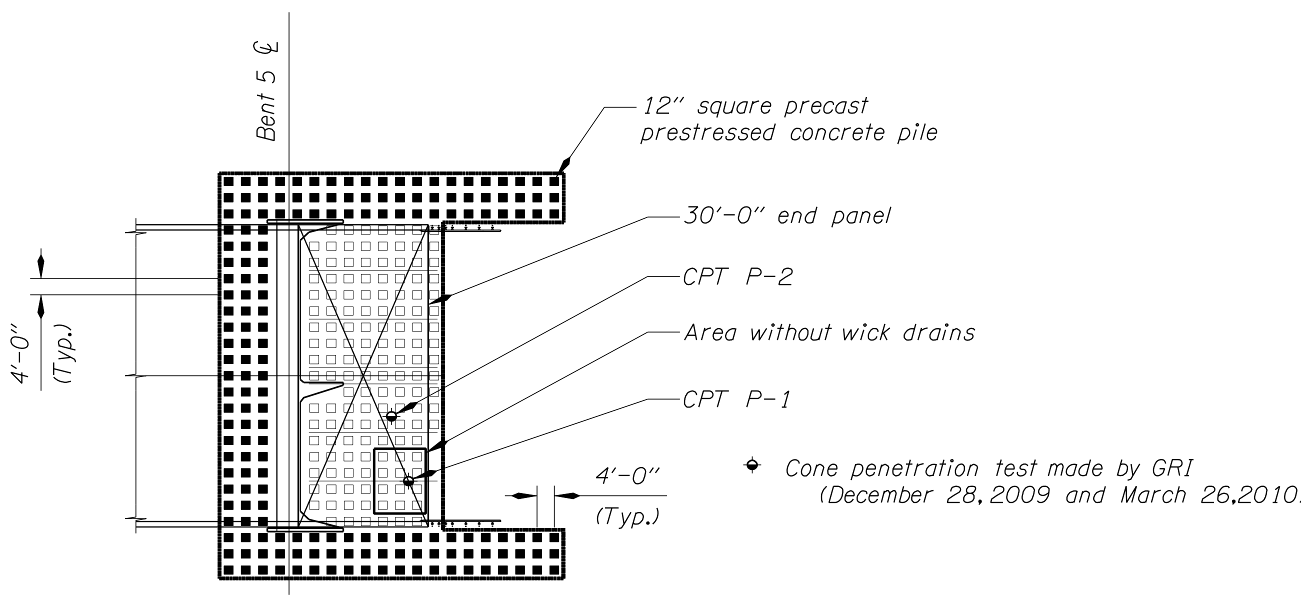

Fig. 4 – Plan View of Shear Pile Installation at Bent 5

The AASHTO Guide Specifications for LRFD Seismic Bridge Design [4] identify 'Permissible ERE's that Require Owner's Approval' and allows an owner to approve the use of 100% of the passive abutment resistance strength of the abutment backfill as a part of the Earthquake Resisting System (ERS). This ERE application uses the abutment backfill as an energy dissipation mechanism in the ERS. Longitudinal and transverse seismic forces from the mass of the bridge are transferred to the abutments through a continuous superstructure.

Within the zone of backfill surrounding the PCPS concrete piles, the existing roadway embankment (composed of very soft to soft silt) was replaced with a well-compacted granular material to provide a quality abutment backfill material. This backfill material transfers the longitudinal forces from the bridge abutment to the shear pile as shown on Figure 5.

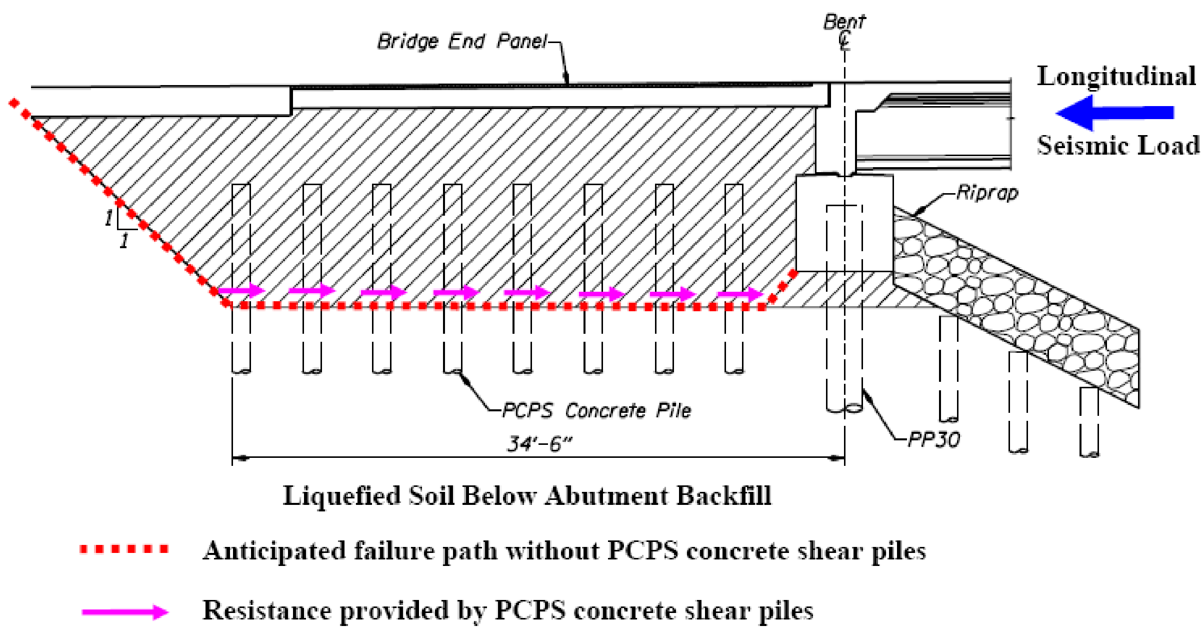

Fig. 5 – Section View of Abutment

Using the abutment backfill as an ERE for this bridge had the benefits of minimizing the interior bent substructure and accommodating a short In-water Work Window (IWW) resulting from environmental requirements. Construction at the abutment was outside the active channel and significant portions of the abutment construction were allowed to take place outside of the IWW.

PREFABRICATED VERTICAL DRAINS TO ENHANCE GROUND IMPROVEMENT

During design, it was recognized that installation of the large number of 12-in.-square concrete displacement piles at the relatively close spacing of 4 ft on-center would likely result in some improvement of the soil strength and increase the resistance to liquefaction of these soils during an earthquake. To take advantage of the anticipated ground improvement, prefabricated vertical drains (wick drains) were installed in the soil between the concrete piles to relieve pore water pressure that develops during pile driving. This had the effect of dynamically compacting and densifying some of the soil.

Cone penetration testing was competed before and after installation of the displacement piles as a means to evaluate the soil strength where closely spaced displacement piles were installed at Bent 5. Densification from ground improvement can be evaluated by comparing tip resistance from CPT probes completed before and after the ground improvement (see Figure 6 and 7). For comparison, locations with and without wick drains were evaluated using CPT probes prior to installation of the piles in December 2009 and after installation of the piles in March 2010. These locations are shown on Figure 4 as CPT P-1 and CPT P-2.

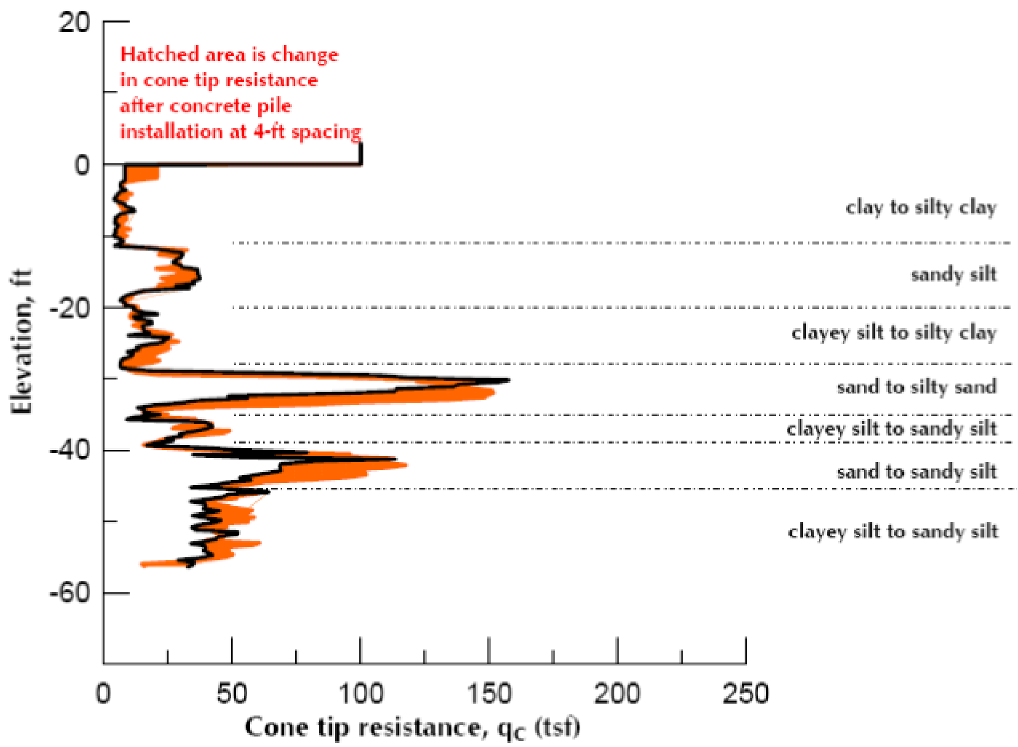

Fig. 6 – CPT Tip Resistance Without Wick Drains

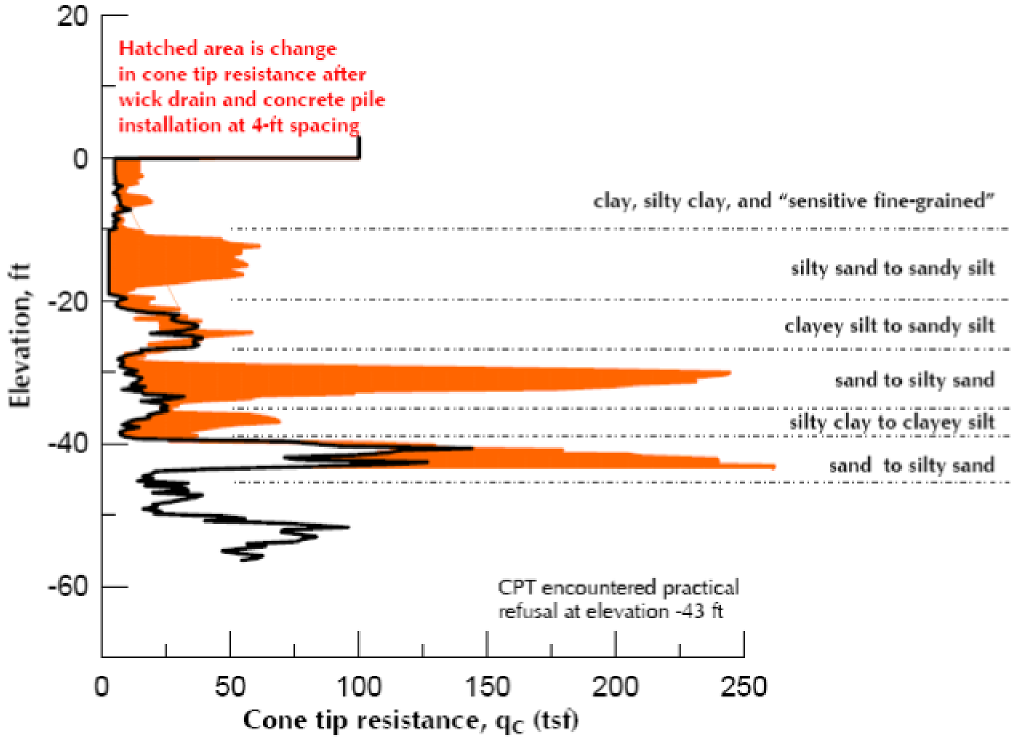

Fig. 7 – CPT Tip Resistance With Wick Drains

Based on the results of this evaluation, the installation of closely spaced piles resulted in no appreciable improvement to soil strength/density in areas without wick drains. In areas where wick drains were installed, moderate to significant gains in tip resistance were observed within zones of sandy material after pile installation. For future projects, wick drains may be considered as a method to enhance ground improvement in the sandy portions of interbedded sand and silt sediments when installing closely spaced displacement piles.

LESSONS LEARNED

The existing bridge is skewed at 45 degrees to align the bent centerline with Millport Slough. Consideration was given to making the new bridge fit the same skew, however, it was eventually realized that a skewed bridge was problematic for design. With the anticipated lateral spreading loads on the substructure elements, the substructure would have to be designed to resist rotation of the bridge in plan view as depicted in Figure 8. It was determined that this additional load combined with the additional substructure construction complexity and cost would be best avoided with a longer, but simpler bridge with no skew. Stream and debris raft pressures were determined to be minimal compared to lateral spreading loads and did not necessitate a skewed bridge. Site grading for the longer un-skewed bridge could be modified to make the general direction of lateral spreading at the abutments parallel with the bridge centerline. With forces induced by lateral spreading oriented near parallel to the bridge centerline, large lateral spread loads can be transferred to the opposite end of the continuous concrete bridge and resisted by the abutment backfill.

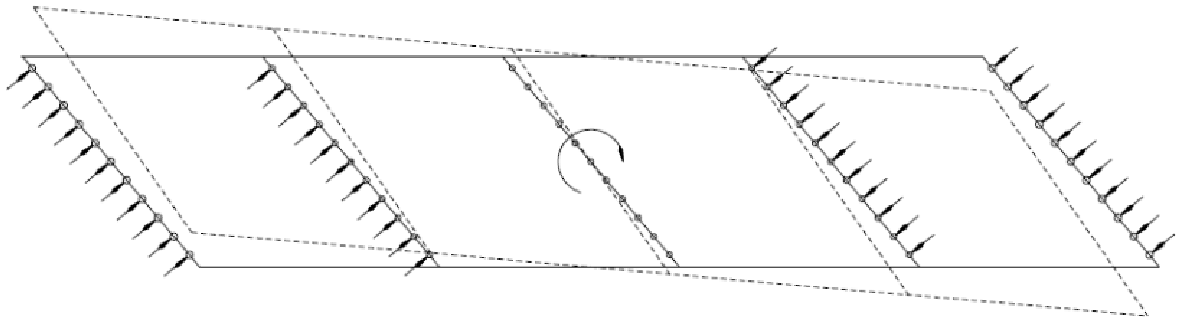

Fig. 8 – Rotation of a Skewed Bridge from Lateral Spread Loads

CONCLUSIONS

The liquefaction and lateral spreading mitigation solution used at this site was developed for a unique problem. The environmental objectives of this project required an innovative approach. The shear pile concept used at the Millport Slough Bridge is another tool for consideration by the design community for lateral spreading mitigation solutions.

The substructure of the interior bridge bents was significantly reduced by designing for the transfer of seismic longitudinal forces through the abutment backfill into PCPS concrete piles. This application of the shear pile concept as an earthquake resisting element required a collaborative, iterative process between the structural and geotechnical engineers during design.

As demonstrated through before and after CPT results, closely-spaced displacement piles can be used to mitigate liquefaction in the sand and sandy portions of interbedded sand and silt when combined with wick drains to dissipate pore water pressures generated during pile installation.

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