Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0713

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Timber compaction piles as part of seismic retrofit for a 110-year old railway bridge

Pieux de compactage du bois dans le cadre d'une modernisation sismique pour un pont ferroviaire de plus de 110 ans

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ABSTRACT: A 100-year-old railway bridge constructed across the Fraser River in British Columbia, Canada has performed remarkably well and is currently in service. The bridge is located close to the Cascadia Subduction Zone- one of the most seismically active areas in the world. The bridge piers within the river and south riverbank are supported on grout filled timber caissons and timber piles founded in Fraser River Sand. Ground response, liquefaction and seismic deformation analyses were performed to assess the seismic performance of the bridge and to develop a retrofit scheme. During the design earthquake, the sand will liquefy and the liquefaction induced displacements will cause significant damage to the river piers. The selected retrofit is to support the superstructure with deep, large diameter piles. In addition, Ground Improvement (GI) would be implemented to densify the soil surrounding the piles and mitigate the effect of liquefaction induced displacements. Timber compaction piles were selected due to the owners' requirement for unimpeded rail traffic during GI, protection of the environment and control of construction induced movements. Following a successful timber compaction pile trial area, production piling was carried out. This paper focuses on the key challenges faced in the design, planning and construction of the GI seismic retrofit.

RÉSUMÉ: Un pont ferroviaire de plus de 100 ans construit sur le fleuve Fraser en Colombie-Britannique Canada, est aujourd’hui en état remarquablement et toujours en service. Le pont est situé près de la zone de subduction « Cascadia » - l'une des zones sismiques les plus actives dans le monde. Les piliers du pont du côté de la rivière et de la rive sud sont soutenus par des caissons en bois remplis de coulis et des pieux de bois fondés dans le sable du fleuve Fraser. Pendant un séisme de conception, le sable se liquéfiera et les déplacements induits par la liquéfaction causeraient des dommages importants aux quais du fleuve. Des analyses de la réponse au sol, de la liquéfaction et de la déformation sismique ont été effectuées afin d'évaluer les performances sismiques du pont et d'élaborer un plan de modernisation. La modernisation choisie est de soutenir la superstructure avec des pieux de grand diamètre. En outre, l'amélioration du sol (GI) serait mise en œuvre pour densifier le sol entourant les pieux et atténuer l'effet des déplacements induits par la liquéfaction. Les pieux de compactage du bois ont été sélectionnés en raison de l'exigence des propriétaires pour ne pas affecter le trafic ferroviaire durant l’amélioration du sol, la protection de l'environnement et le contrôle des mouvements induits par la construction. À la suite d'une zone d'essai réussie de la pile de compactage du bois, des empilages de production ont été effectués. Le présent document met l'accent sur les principaux défis rencontrés lors de la conception, la planification et la construction de la modernisation sismique de l’amélioration du sol.

Keywords: Ground Improvement; Timber Compaction Piles; Liquefaction

1 INTRODUCTION

A railway bridge in British Columbia Canada was constructed in the 1900s across the Fraser River to provide a railway route between two cities separated by the river. The bridge is 1050 m-long and is supported on eleven piers, of which nine piers are currently within the river. Piers 1 to 5 are founded on concrete filled caissons, and Piers 6 to 11 are founded on concrete-filled timber cribs with timber pile foundations. Piers 2 to 11 were constructed of masonry granite blocks infilled with unreinforced mass concrete. The bridge and the original foundations have performed remarkably well since construction.

Pier 11, which is the main focus of this paper, is located at the southeast bank. Figure 1 shows an aerial view of the south side of the bridge and Figure 2 shows the south riverbank.

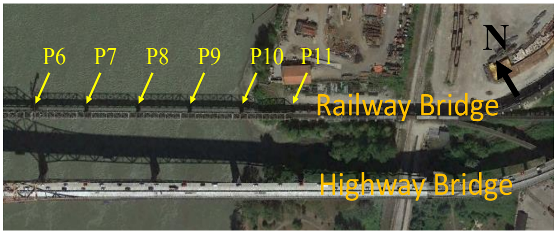

Figure 1. Section along railway bridge

The seismic performance of the bridge was assessed under the 475 year return period design earthquake. The ground response and liquefaction assessments indicated that the upper portion of river sands were potentially liquefiable, and the foundation soils could undergo lateral spreading. Assessments of the existing piers and foundations showed that the existing foundations, which have timber piles within the liquefiable soils, could undergo significant movements due to the liquefaction-induced soil displacements, potentially leading to bridge collapse.

The proposed geotechnical retrofits for the Piers 6 to 11, which are currently supported on relatively short timber piles included: 1) addition of two large diameter steel pipe piles at each pier; and 2) ground densification using timber compaction piles at the riverbank Pier 11. This paper focuses on the timber compaction pile component of the geotechnical retrofit at Pier 11. It also assesses the effectiveness of timber compaction piles as a ground densification technique to improve potentially liquefiable soils.

Figure 2. Pier 11

2 SEISMIC DESIGN CRITERIA

A no collapse under a 475-year return period earthquake was adopted as the seismic design criterion for the retrofit of the bridge.

The seismic hazard at the bridge site arise from the following three sources: 1) local crustal earthquakes occurring on the North American Plate; 2) deep in-slab earthquakes occurring on the subducting Juan de Fuca Plate; and 3) Cascadia subduction interface earthquakes occurring at the interface between the subducting Juan de Fuca plate and the North American plate.

The Uniform Hazard Response Spectra (UHRS) corresponding to the 475 year return period design earthquake were obtained from the Geological Survey of Canada (Halchuck et al., 2015). The Peak Ground Acceleration (PGA) was 0.18g for ground conditions with shear wave velocity, V_{s30} between 360 and 760 m/s. For the liquefaction assessment an earthquake with magnitude of M7.5 was used for each crustal and in-slab earthquakes, and a magnitude M8.75 was used for subduction interface earthquakes based on results from seismic de-aggregation analyses.

Three suites of time histories representative of crustal, in-slab and interface earthquakes were selected and scaled to match the scenario spectra for each type of earthquake. The scenario spectra being the component of the UHRS from each of the source earthquakes. These time histories were used in the site response analyses.

3 SUBSOIL CONDITIONS AND FOUNDATIONS

The foundation soils consist of glacial till overlain by marine silt and Fraser River deposits. The river deposits include interbedded sand and silt overlain by loose to dense clean sand. Figure 3 presents the geological cross section along the bridge alignment.

The clean Fraser River sand deposits range in thickness from 20 m to 40 m on the north and south sides of the bridge. Cone Penetration Tests (CPTs) and Standard Penetration Tests (SPTs) obtained during various site investigations indicated that the upper sand layer is loose, becoming denser with increasing depth.

The interbedded sand and silt layers were characterized using the CPT soil behavior type index, I_c (Robertson and Wride, 1998). This showed that approximately 70% of the interbedded sand and silt had an I_c value of less than 2.6. As such, these soils were assumed to behave as a "sand-like" material and were treated as a granular material in the liquefaction assessment.

The marine silt ranges in thickness from about 5 m to 20 m along the bridge alignment. CPT and SPT data indicates that the material is stiff to very stiff. The glacial till is very dense and underlies the marine silt deposits.

4 SITE RESPONSE AND LIQUEFACTION ANALYSES

Amplification of ground motions and the onset of liquefaction was the main concern for the seismic retrofit design. One-dimensional, equivalent linear site response analyses were carried out at three representative soil columns to determine the peak horizontal accelerations and shear stresses within the soil. These analyses were conducted using the software ProShake (EduPro, 2017). Figure 3 shows the results of the liquefaction assessment for the 475-year earthquake based on the scenario earthquakes. At this site, the crustal and in-slab scenario ground motions produce a larger cyclic stress ratio (CSR) response than the subduction interface ground motions.

The liquefaction assessment of the Fraser River deposits was carried out in accordance with the simplified method recommended by Boulanger and Idriss (2014), which is considered an update of the method described in Youd et al. (2001). In these methods, CSRs induced by the design earthquake are compared with the cyclic resistance ratios (CRRs) derived from databases of field observations.

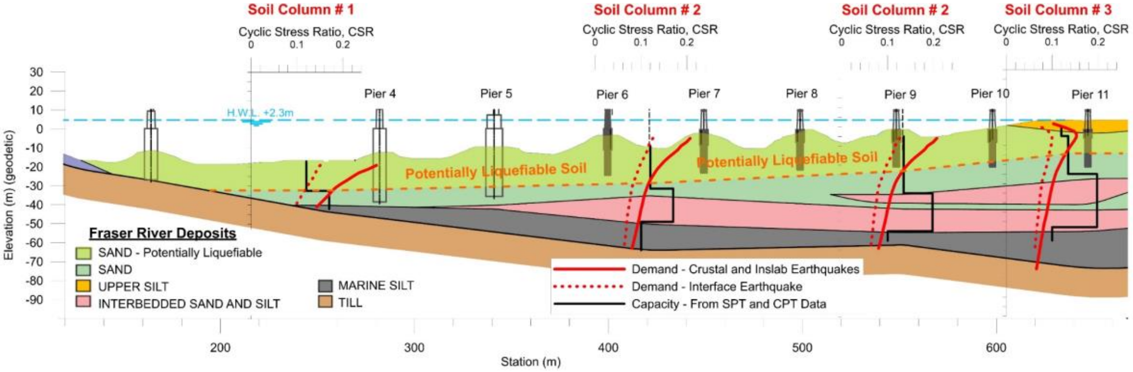

Figure 3. Geological Section and Results of Liquefaction Assessment

At depths where the CSR exceeds the CRR, the soil is considered to be potentially liquefiable. The extent of potentially liquefiable soils is presented on Figure 3.

As part of the liquefaction assessment, the minimum CPT tip resistances required to prevent liquefaction were calculated and are presented on Figure 4. Resistance criteria for sand with less than 10% fines (i.e. materials finer than 0.075 mm) and with 10 to 20% fines are given. The CPT tip resistances are based on a factor of safety of 1.3 against liquefaction triggering.

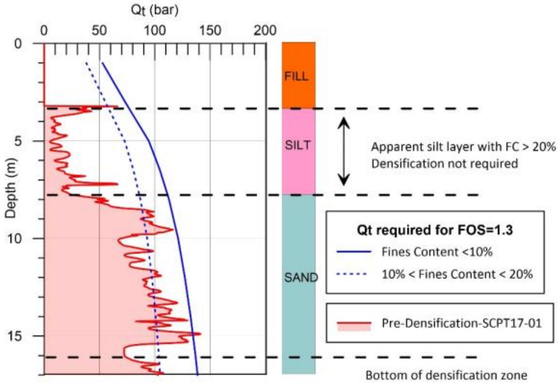

Figure 4. Required CPT tip resistance

5 SEISMIC RETROFIT STRATEGY

The existing bridge foundations have performed remarkably well under static conditions and railway loading. This includes changing bathymetry due to flood events as well as ship impact loads. It was therefore assumed that the existing foundations would continue to support the piers and superstructure under static conditions, but could lose capacity at the onset of the earthquake. The proposed retrofit would therefore be designed to pick up the vertical loads during the design earthquake and in the post-earthquake condition.

During the design earthquake, the sand will liquefy around the existing pier foundations, resulting in large settlements and loss of bearing capacity. Additionally, the slope of the river bank and sloping riverbed will cause significant lateral displacement resulting in intollerable horizontal displacements of the piers.

The solution to prevent these large displacements was to install large diameter piles upstream and downstream of the piers into a non-liquefiable stratum. These piles would be connected to the existing piers with a steel collar frame above the river level.

At the south riverbank between Piers 10 and Pier 11, the sloping ground towards the river causes additional liquefaction induced displacements and Ground Improvement (GI) was considered in addition to the large diameter piles to reduce the potential for lateral spreading around each of the large diameter retrofit piles.

The retrofit scheme comprising the GI and the large diameter piles at Pier 11 is presented on Figure 5. The ground improvement was carried out prior to the installation of the large diameter piles.

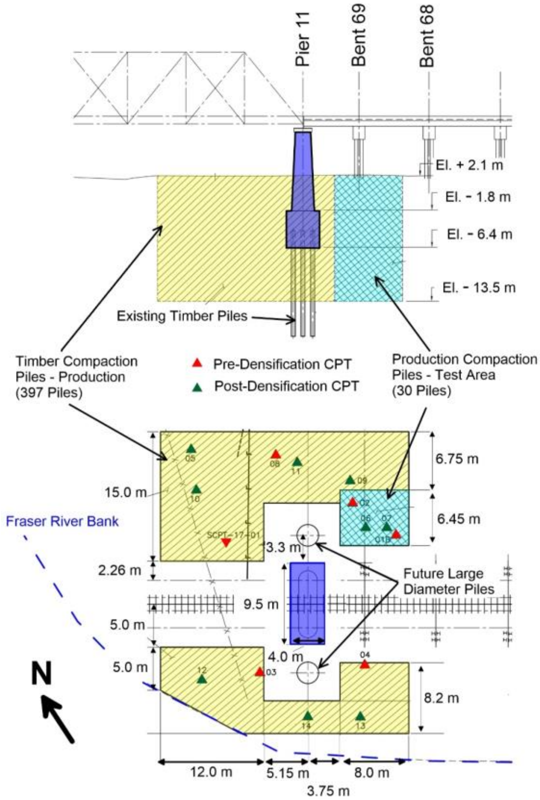

Figure 5. Pier 11 retrofit design

6 GROUND DENSIFICATION USING TIMBER COMPACTION PILES

6.1 Selection of Timber Compaction Piles

Compaction Grouting, vibro-replacement and timber compaction piles were considered for the GI around Pier 11.

When evaluating the options, the main considerations were: 1) the owners requirement for unimpeded rail traffic during construction; 2) control of constuction induced movements and vibrations to the existing structures; 3) protection of Fraser River habitat and the environment; 4) the ability to work adjacent to existing stuctures, utilites and trees; and 5) cost.

Compaction grouting could be carried out from a relatively small drill rig with a short drilling mast. This was considered a possible option because all work could be carried out below the railway track level and there was no risk of equipment swinging onto the tracks or interference with rail traffic. However, this method was ruled out due to the environmental impact on the watercourse and high cost.

Vibro-densification was considered as a relatively inexpensive option. However, it was ruled out due to potential adverse effects of releasing sediments into the Fraser River, and settlement of the exising structure.

Timber compaction piles were chosen as the viable method satisfying the requirements for selection described earlier. The method does not require water, produce wastewater, or require cement or grout. The method can also be used to densify soils adjacent to existing trees and buried utilities as piles could be driven in close proximity to trees and utilities without adversely impacting them. Settlement of the existing structure due to pile driving was expected to be tolerable based on past experience; however, a test pile program with extensive monitoring was undertaken during piling to check and evaluate.

6.2 Compaction Test Pile Program

A compaction test pile program was conducted on the northeast edge of Pier 11 to evaluate: 1) the effectiveness of the timber compaction piles as a ground densification method; 2) verify the spacing and pattern of piles; 3) assess the driveability of piles; and 4) evaluate the impact of pile driving on the existing bridge structure.

Thirty timber compaction piles were driven with a 2310 kg drop hammer and an ICE I-19 diesel hammer with a maximum rated energy of 66 kJ. The drop hammer was used to install the piles to between 4 m and 9.8 m depth and the diesel hammer was used to drive the piles to the design depth of 15.2 m. Twenty of the piles were driven to the design depth and 9 piles were driven to practical refusal between 12.2 m and 14.9 m depth. The contractors refusal criteria was 8 blows per 25 mm over the last 150 mm of driving (at the maximum rated energy). Piles were also terminated when the top of the pile split or splintered. The timber piles were untreated round wood (Hemlock with bark) with a minimum tip diameter of 225 mm. The piles were driven in the trial area with a 1.2 m equilateral triangular pattern. The piles were driven in single lengths without splices.

Figure 6 shows a comparison of the pre and post-densification CPTs in the test area. It also shows the cone tip resistances required to prevent liquefaction with a factor of safety of 1.3 for clean sand and sand with 10-20% fines content.

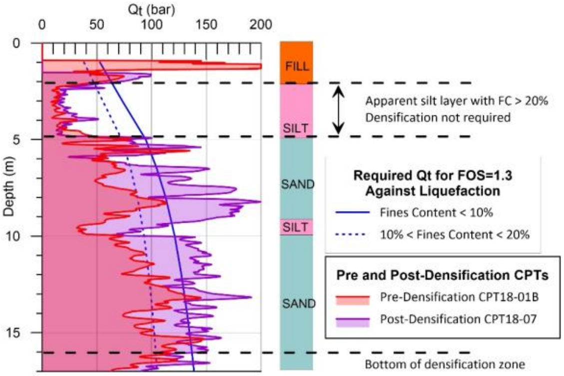

Figure 6. Test Area –Pre/Post Densification CPTs

Based on the results from the test pile program, the same pattern and spacing and methodology (equipment and procedure) was used for piling in the production areas.

6.3 *Production Piles*

A total of 246 piles were driven in the production area northeast of the rail track and a total of 151 piles were driven on the southwest of the rail track. All production piles were driven in single lengths without splices.

Six post densification CPTs were conducted in the production area to quantify the effectiveness of the densification. The CPTs were located in the centroid of the compaction piles. Figure 7 shows a comparison of the pre- and post-densification CPT tip resistances.

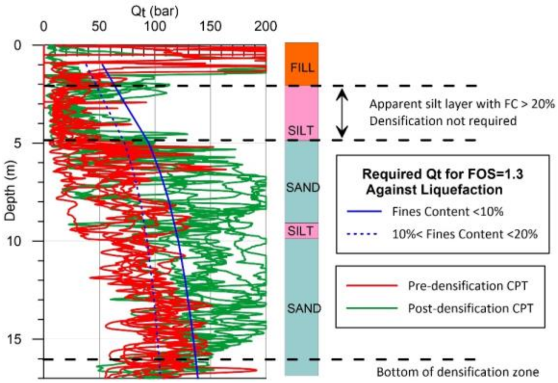

Figure 7. Production Area - Pre and Post Densification CPTs

In general, the specified tip resistances were achieved, and the design intent of the densification satisfied.

6.4 *Issues During Construction*

The owner required that the railway bridge remain in operation during the ground improvement work. As such, the pile installation immediately adjacent to the track had to be paused as trains were passing. The frequency of trains ranged from 30 to 35 trains per day. The diesel piling hammer was able to be shut down immediately when a train was approaching. Figure 8 shows the proximity of the piling equipment to the operational track.

Figure 8. Pile driving adjacent to railway track

The GI area southwest of the rail track had multiple timber piles located on the riverbank and within a tributary of the Fraser River. Materials or surface water from the GI area were not allowed to enter the watercourse. These timber piles were installed during low tide with containment booms surrounding the working area. Timber piles were driven between trees on the riverbank rather than removing the trees. The integrity of the bank was maintained during pile driving.

Figure 9. Pile driving adjacent to the river bank

Both underground and overhead utilities were in the vicinity of the GI area. Underground utilities including a fire suppression water line (Figure 10) and a power supply line for the bridge were located and daylighted prior to pile driving. The layout of the timber piles needed to be adjusted and one pile eliminated to avoid impacting the fire suppression water line. An overhead communication cable which intersected the GI area had sufficient slack to be held away from timber piles during driving.

Figure 10. Pile driving adjacent to utilities

7 CONSTURCTION MONITORING

7.1 *Displacement Monitoring*

The contractor monitored the vertical and horizontal movements of Piers 10 and 11 and bridge Bents 67 to 69 located south of Pier 11.

Monitoring points were installed on the structure near the ground and close to the track level on both sides of the track. Typical locations of the monitoring points are shown on Figure 11.

Figure 11. Typical monitoring points

During the test pile program. monitoring was performed after the installation of two piles, four piles, seven piles, ten piles, twenty piles and thirty piles as there were uncertainties in the impact of pile driving on the existing structure. Following a successful trial, the monitoring frequency was changed for the production piling. Initially, readings were taken three times during the shift regardless of working area (morning, mid-day and end of shift) but was reduced to daily as no movement trend was observed. Monitoring reverted back to three times daily for certain critical piles.

The monitored settlement of Pier 10, Pier 11, Bent 67, Bent 68 and Bent 69 were less than 5 mm after the completion of piling. The measured horizontal movement either in the northing or easting direction at Piers 10, Pier 11, Bents 69, Bents 68 and Bent 68 were less than 17 mm. The greatest movement was observed at Pier 11 and Bent 69, which are located nearest to the GI area.

7.2 *Vibration Monitoring*

Vibration monitoring on the adjacent vehicle bridge pier located approximately 45 m from the GI area was conducted during the timber piling using the 2310 kg drop hammer and ICE I-19 diesel hammer. Vibration monitoring was conducted using an Instantel Micromate vibration monitor and the vibration monitor sensor was placed directly on the concrete foundation of the highway pier during monitoring. The typical ‘background’ vibration level or Peak Particle Velocity (PPV) was found to be approximately 1 mm/s. During piling, there was negligible change in the measured vibration compared to the baseline readings. The recorded PPVs were typically 1 mm/s and no readings exceeded 2 mm/s.

8 SUMMARY AND CONCLUSIONS

A 110-year-old railway bridge constructed across the Fraser River in British Columbia, Canada has performed remarkably well and is currently in service.

The bridge piers within the southside of river and at the south riverbank are supported on grout filled timber caissons and timber piles founded in

Fraser River Sand. During the design earthquake, the sand will liquefy and the liquefaction induced displacements will cause significant damage to the river piers.

Ground response, liquefaction and seismic deformation analyses were performed to assess the seismic performance of the bridge and to develop a retrofit scheme. The selected retrofit scheme included ground improvement, using timber compaction piles to mitigate the effect of liquefaction induced displacements at the south riverbank and installation of large diameter piles as part of structural retrofit for the bridge piers. This paper focussed on the ground improvement using timber compaction piles.

Timber compaction pile construction commenced in a trial area adjacent to Pier 11 to assess the effectiveness of the timber compaction piles in densifying loose Fraser River Sand and driveability of piles, check the pile spacing and pattern, and impact of pile driving on the existing bridge. The trial demonstrated that the required densification was achieved with 225 mm tip diameter timber piles with an 1.2 m equilateral triangular pattern. It also demonstrated that installation of the piles had a minimal effect on the existing structures.

Following the successful trial, production piling was carried out. During production, the piles were successfully driven adjacent to the operating railway, at the edge of the riverbank and adjacent to burried utilities. The required densification to prevent liquefaction triggering was generally achieved. Monitoring of the existing structures during constuction indicated that the structures were not adversly affected by the timber compaction piling.

Owners' requirement for unimpeded rail traffic during construction, potential environmental impact on adjacent Fraser River and its habitat, construction induced movement on existing bridge structure and underground utilities and construction cost, effectiveness of densification technique and verifiability of densification posed significant constraints during the selection of suitable technique for ground densification. Starting with a trial for assessment and verification, the timber compaction piles proved to be a viable technique to overcome these constraints and achieve the required densification of the soils.

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