Retrofit of a pile-supported bridge in soft clay damaged by failure of adjacent soil stockpile

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ABSTRACT
The Roger Pierlet Overpass, built in 1975, was displaced and damaged in November 2004 by foundation soil movement caused by failure of a large soil stockpile placed adjacent to the bridge. The concrete bridge is supported on long precast concrete piles driven through soft marine clay to toe bearing in very dense till-like soils. The soil failure caused cracks in pier columns and pile cap beams, displaced structural elements, and significantly damaged the precast concrete piles. Shortly after the damage was discovered, temporary support towers were erected to provide support for the bridge decks and to allow traffic to safely continue on the bridge. Permanent retrofit of the bridge included strengthening of columns and beam/column joints, extension of existing pile caps, and addition of steel pipe piles to replace the damaged concrete piles. This paper presents details of the damage, subsequent ground investigations, and the temporary and permanent retrofits of the bridge and its foundations.

RESUMEN
El paso elevado de la autopista Pierlet Roger, construida en 1975, fue desplazada y dañada en Noviembre de 2004 por el movimiento de las fundación de suelo causado por la falla del talud de una gran pila de almacenamiento de suelo colocada junto al puente. El puente de hormigón está soportado en largos pilotes de hormigón prefabricados que penetraron arcillas marinas blandas y acabados en suelos glaciares muy densos (till-like). El derrumbe de suelos creó grietas en las columnas de los pilares y vigas de la losa de fundación de los pilotes, desplazó elementos estructurales y dañó significativamente los pilotes de hormigón prefabricados. Poco después de que el daño fue descubierto, se erigieron torres de soporte temporal para apoyar las cubiertas del puente y para permitir de que el tráfico en el puente continuara con seguridad. La readaptación (retrofit) permanente del puente incluyó el fortalecimiento de las columnas y las articulaciones viga/columna, extensión de las losas de fundación de pilotes existente y la implementación de pilotes de tubo de acero para reemplazar los pilotes de hormigón que fueron dañados. Esta publicación técnica presenta los detalles de los daños, investigaciones posteriores del terreno y las readaptaciones temporales y permanentes del puente y sus fundaciones

1 INTRODUCTION

The Roger Pierlet Overpass is a 410 m long bridge built in 1975 on Highway 15 over the CP Railway in Cloverdale, British Columbia (see Fig. 1). The site is underlain by a deposit of soft and compressible marine clay, up to 50 m deep, overlying very dense till-like deposits of sand, gravel, silt and clay. The concrete bridge structure is supported on precast concrete piles toe bearing in the till-like soils.

In November 2004, the south approach of the bridge was damaged by foundation soil movement caused by failure beneath a soil stockpile placed adjacent to the east side of the bridge. The soil failure displaced the pile-supported piers by as much as 425 mm horizontally. Substantial cracking of pier columns, foundation tie beams, and piles (inspected at underside of pile caps) resulted. Several deck expansion joints developed large separations. The cantilevered steel sidewalks and roadway railings were also damaged, resulting in temporary closure of the sidewalk.

This paper describes the damages suffered by the existing bridge and its foundations due to the soil failure, along with the subsequent ground investigations, testing and monitoring, and the design and construction of temporary and permanent repair measures.

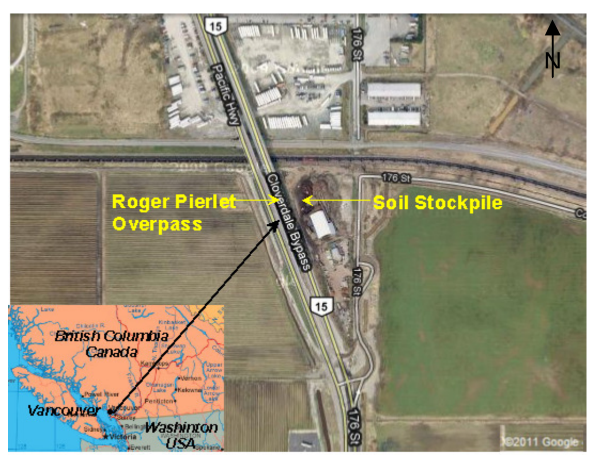

Figure 1. Location map of Roger Pierlet Overpass in Cloverdale, Surrey, BC

2 EXISTING OVERPASS STRUCTURE

The existing Roger Pierlet bridge structure comprises 20 simply supported 21 m long spans. Each span consists of a reinforced concrete deck on 6 precast concrete I-girders supported by a concrete pier or bent. The 19 piers are similar and consist of reinforced concrete piercaps on a pair of circular concrete columns, each founded on a separate pile cap with three, 305 mm wide hexagonal-shaped precast concrete “Herkules-type” piles in a single row laid out parallel to the bridge alignment. A reinforced concrete tie beam joins the top of the pile caps at each bent. The bridge deck has alternating fixed and expansion joints at the piers. The sidewalks on each side of the deck are constructed of open steel grating surface supported by single angle steel members cantilevered from the concrete deck.

The marine clay underlying the site is part of the Cloverdale Sediments. Typical of the clay in this region, except for the top few metres of crust, it is normally consolidated to very slightly over-consolidated. At this site, the clay comprises soft to firm, highly sensitive, low to medium plastic silty clay (CL-CH) with:

Plasticity Index	10 to 30%
Liquid Limit	30 to 55%
Moisture Content	30 to 60%

Peak vane shear strengths generally vary from about 25 kPa at 6 m depth to 50 kPa at 36 m depth.

The bridge piers and north abutment are supported on precast concrete piles that were driven through the soft clay to practical refusal in the till-like soils. The as-built pile lengths vary from 40 m to 54 m below cutoff. The bridge south abutment is supported on spread footings on ground improved by temporary preload/surcharge and sand drains.

The weak and compressible characteristics of the clay were recognized during original design, which specified staged construction with sand drains and preload treatment over 3 years for the abutment fills. Despite this awareness, during original construction of the bridge, a failure occurred on July 31, 1971 when a portion of the south abutment fill outside the sand drain area was raised from a height of 3.5 m to 4.9 m (Crawford and DeBoer, 1987). Back analysis of the embankment failure indicated an average shear strength in the clay of only 16 kPa, about 65% of the value used for design. This failure illustrated the highly sensitive nature of the clay to disturbance caused by shear loading.

3 OBSERVED DAMAGES

On or about November 14, 2004, a stockpile of topsoil, located on the property immediate east and running the full-length of the south approach of the bridge, failed. The soil failure pushed up the ground level between Bents 5 and 6 to a height of 3 to 4 m, and to a lesser height between Bents 6 and 7 (see Figs. 2 and 3). The bridge centerline moved horizontally by more than 150 mm between Bents 4 and 7, with up to 428 mm at Bent 6, resulting in a noticeable kink in the structure at this location. Fig. 4 shows the surveyed permanent horizontal displacements of the pier centreline after the event.

Figure 2. Soil pushed up between Piers 5 and 6 (looking north)

Figure 3. Soil pushed up near Pier 6 (looking south)

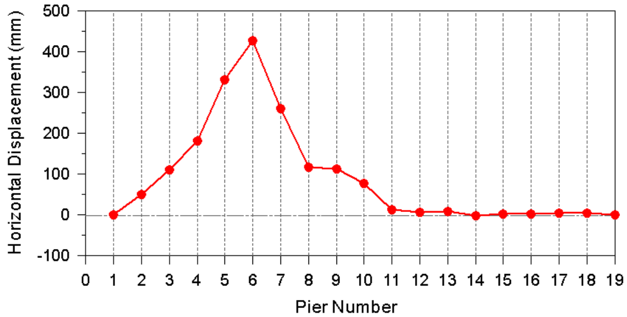

Figure 4. Horizontal displacement profile of pier centreline (Note pier numbering starts from south end of overpass)

In addition to the transverse pier movements, significant tilting or rotation of pier columns was observed at Piers 5 to 7. Top to bottom relative displacements of up to 45 mm transversely and up to 84 mm longitudinally, were measured. Substantial cracks on pier columns and pile cap beams were observed (see Fig. 5). Several girders at Pier 6 also shifted over the bearing pads, reducing the available bearing seat lengths (see Fig. 6).

Figure 5. Cracks in pile cap beam and column at Pier 6

Figure 6. Displaced girder at Pier 6 (looking west)

The deck expansion joint at Pier 6 had opened to 147 mm on the west side compared to 14 mm on the east (see Fig. 7). On the other hand, the joint at Pier 8 opened the opposite way, and was measured at 72 mm on the east side and 14 mm on the west (see Fig. 8).

The sidewalk grates or panels between Piers 2 and 10 sustained damage due to the pier movements, and most noticeably at Pier 6, where a support bracket was bent. Sidewalk pedestrian handrails and roadway railings were pulled apart at Piers 6 and 8.

Figure 9 summarizes in schematic the damages observed on the south approach of the bridge due to the November 2004 soil failure. Shortly after the event, cracks in the columns, tie beams and exposed piles (described in Section 4) were epoxy injected, the soil stockpile in the adjacent property was re-profiled to a much flatter overall slope, and the heaved soil between Piers 5 to 7 was removed. Despite the displacement and damage, structural assessment showed the bridge to be safe for traffic, but all repair and construction activities were carefully controlled with constant monitoring of the bridge and foundation.

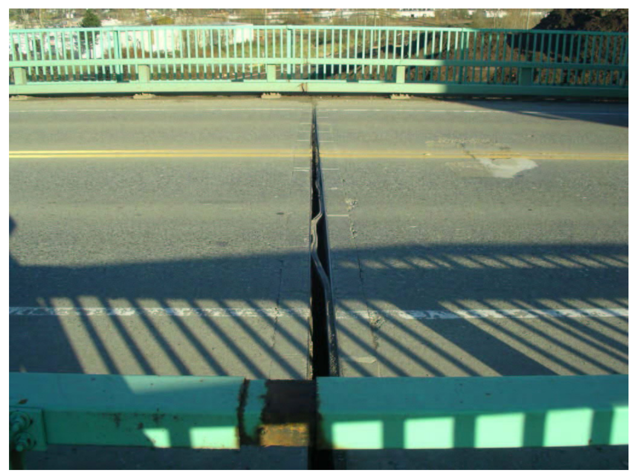

Figure 7. Uneven displacement of expansion joint at Pier 6, and traffic rail pulled apart at the west side (foreground)

Figure 8. Uneven displacement of expansion joint at Pier 8, and handrail pulled apart at the east side (far side)

Note that the November 2004 soil failure also resulted in partial redesign of a new bridge approach on the west side of the existing bridge, which was under construction at the time as part of the Twinning of Roger Pierlet Bridge Project (Yang and Gohl 2006). The new parallel overpass was subsequently completed by a design-build contract in Fall 2006.

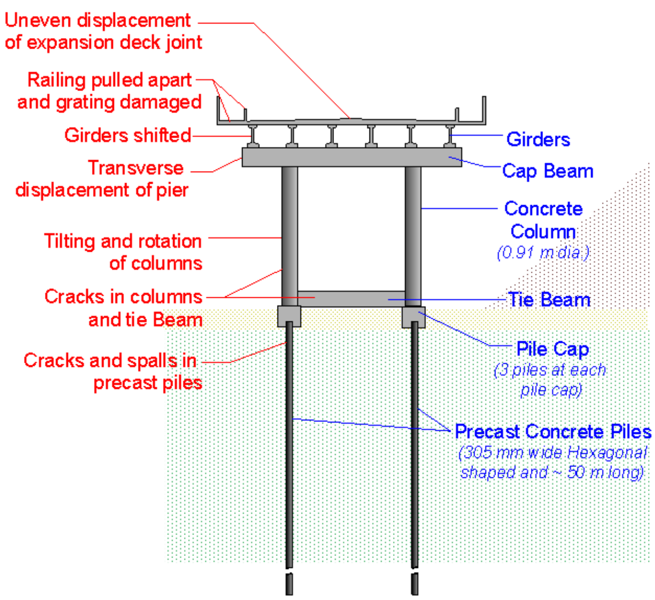

Figure 9. Observed damages on bridge after soil failure

4 PILE INSPECTION AND TESTING

Shortly after the soil failure, selected piles at Piers 4 to 8 were partially exposed by local excavations to about 2.5 m depth for visual inspection and for low-strain integrity testing. Note that only the top 1 m of the pile length below the underside of pile cap was accessible for visual observation. The inspection and testing revealed the following:

1. The visual inspections indicated cracks and spalls in the upper part of many piles on the west side of Piers 4, 5 and 6. Note in particular, that cracking was observed on the west side of the individual piles and spalling on the east side of the piles. The piles on the east side of the pier (adjacent to the soil stockpile), however, did not show any apparent damage in the upper 1 m of the pile length. Figure 10 shows photos of cracks in the top part of concrete piles observed upon excavation.

2. The low strain integrity testing indicated impedance reductions of piles on both the east and west sides of Piers 4 to 8. These impedance reductions suggest presence of partially opened joints and/or concrete cracks, but no evidence of complete pile separation.

Figure 10. Cracks in precast piles at Pier 5 and Pier 6 on the west side

5 POST-EVENT SITE INVESTIGATIONS

Site investigations consisting of cone penetration tests (CPT) and in-situ field vane shear tests were carried out in and around the significantly displaced piers and soil failure area. Inclinometers and piezometers were also installed to monitor lateral ground movement and pore pressures, respectively. Figure 11 shows the locations of the test holes and instrumentation, as well as the approximate outline of the displaced or heaved soil around Piers 5 to 7. Note the soil stockpile was on the east side (bottom of figure) of the bridge.

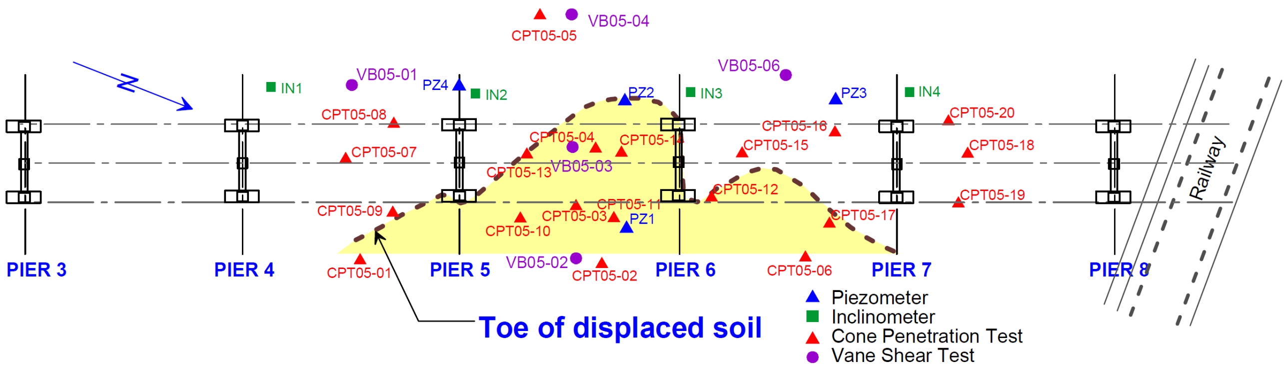

Figure 11. Locations of test holes and instrumentation, and toe of displaced soil

Figure 12 shows the peak undrained shear strength profiles obtained from field vane shear tests carried out inside (red lines) and outside (blue lines) the failure area. The vane shear test results were not able to definitively differentiate between the disturbed clay in the failure area and the undisturbed clay outside the failure area.

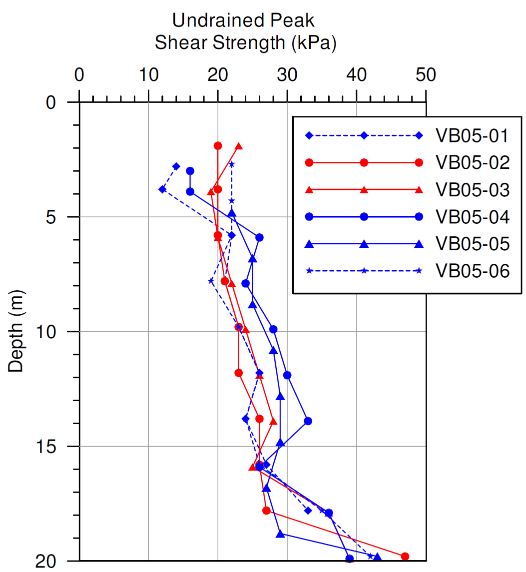

Figure 12. Undrained peak shear strength profiles from field vane shear tests

Figure 13 shows cone tip resistance profiles of the CPTs separated into two groups or plots: within failure area (left plot) and outside failure area (right plot). Note the CPTs within the failure area clearly show absence of the typical 2 m thick clay crust that is evident in the CPTs performed outside the failure area.

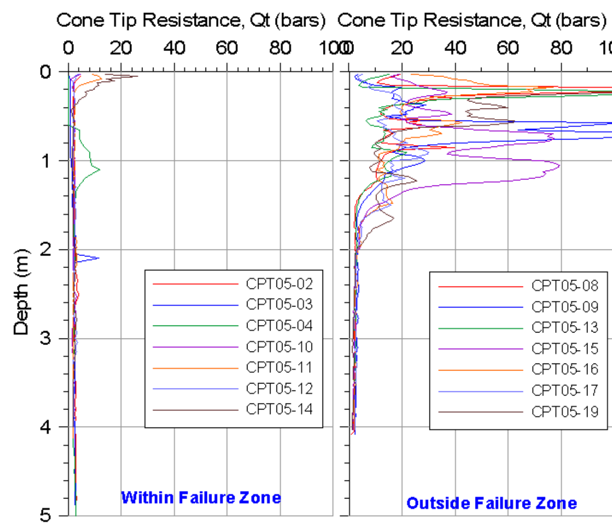

Figure 13. CPT tip resistance profiles

The inclinometer data suggested slight ground displacement (or rebound) to the east, of the order of 20 mm in the upper few metres between January and May 2005, likely due to unloading of adjacent soil stockpile at the neighbouring property. Otherwise, the inclinometer data indicated no further lateral ground movement during subsequent retrofit construction.

The piezometer data indicated high excess pore pressures existed in the ground, even one and a half years after the soil failure, particularly on the east side of the bridge. There was very slight dissipation during that period (see Fig. 14).

movement (lateral spreading) resulting from the soil stockpiling activities at the adjacent property.

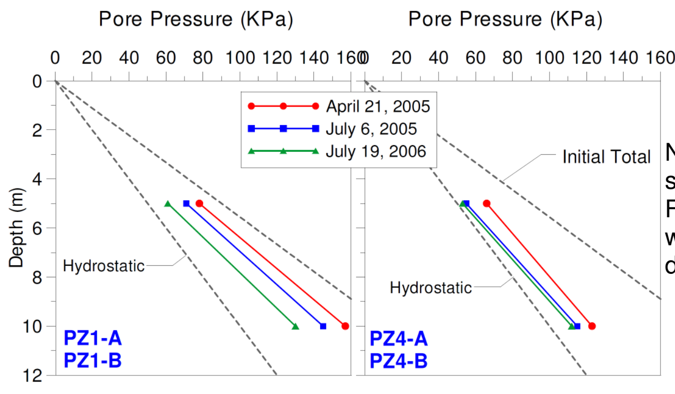

Figure 14. Measured pore pressures in piezometers PZ1 and PZ4

6 GROUND FAILURE MECHANISM

Based on the damage observations and subsequent investigations, the following conclusions of the likely ground failure mechanism were made:

- The topsoil stockpile failure resulted in ground displacements likely along a circular-type slip surface 6 m to 10 m deep beneath the east side of the bridge, and exiting near the west side of the bridge, as illustrated in Fig. 15. This conclusion is supported by the observed soil heave between Piers 5 and 7 following the failure event, comparison of cone penetration test data inside and outside the affected area, high excess pore pressures in the ground as observed in the piezometers, and the observed pile damage.

- The ground failure mechanism would have resulted in soil displacement and loading against the upper portion of the piles and pile caps on the east side, and mostly structural loading from the cross beams to the piles on the west side. This is confirmed by the difference in damage patterns observed on the piles in the east and west sides of the bridge.

- The damaged piles likely have S-shape below 3 m depth. The concrete in the high curvature zones was likely crushed and the pile is expected to behave more like gabions than a precast pile. The damaged piles could still carry existing axial loads, but their future performance is considered unreliable and they are unlikely to perform satisfactorily during earthquake.

- The existing piles in Piers 4 to 7 are damaged. There is also a risk that piles in Piers 3 and 8, which are also adjacent to the topsoil property, are damaged, either from the November 2004 ground failure, or due to prior ground creep movement (lateral spreading) resulting from the soil stockpiling activities at the adjacent property.

Note that the damage to the precast concrete piles is similar to the observations of pile damage reported by Fellenius (1972) based on a case history in Sweden where concrete piles for a building in soft clay were damaged by ground failure due to adjacent surcharge.

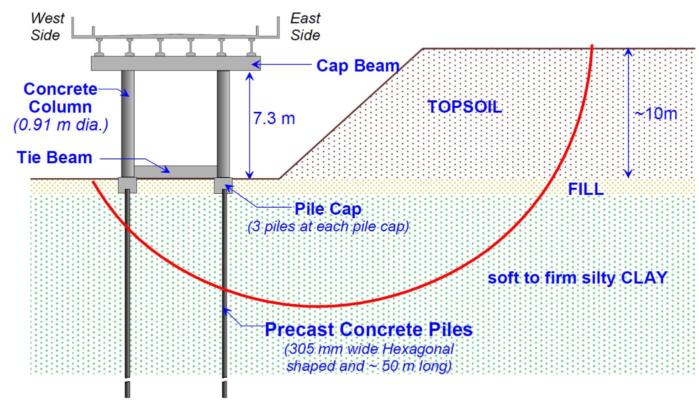

Figure 15. Failure mode of topsoil and bridge pier

7 TEMPORARY REPAIRS

Shortly after the failure, temporary repairs were carried out that included the following measures:

- Temporary shoring towers (using Acrow temporary bridge panels) were erected to support the girders between Piers 4 to 8, as shown in Figs. 16 and 17. The towers were founded on concrete pads on a layer of lightweight pumice fill. The footings were sized to limit bearing pressure to 50 kPa and to minimize settlement. The tower height was adjustable by shims to accommodate expected settlement.

- Longitudinal restrainers were installed between the girder ends at Piers 4, 6 and 8 to prevent loss-of-span failure. The restrainers consisted of Dywidag bars with steel brackets bolted onto the web of the girders.

Figure 18 shows typical time-settlement plots of the temporary tower concrete pads, as well as a location plan. Note the significantly higher settlements recorded on pads within the failure area (red curves), compared to those outside the failure area (blue curves).

The inclinometers and piezometers, as well as structure movement hubs, were monitored constantly during the repair work.

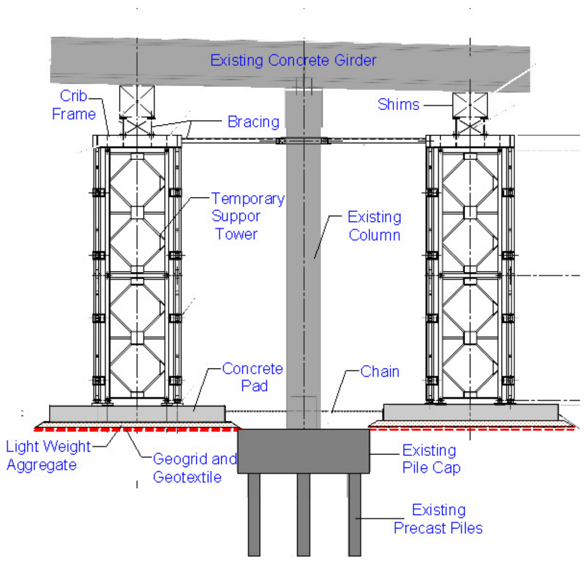

Figure 16. Temporary support towers around pier (longitudinal view)

Figure 17. Temporary support towers as constructed

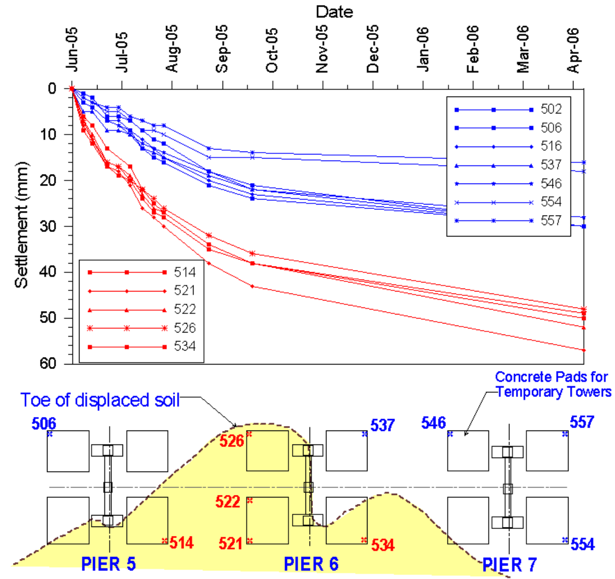

Figure 18. Time vs. settlement plots of the temporary tower concrete pads, and location plan

8 PERMANENT REPAIRS

Permanent repairs to the existing bridge were subsequently designed and consisted of the following features:

- New piles, pile cap extensions and tie-beams at Piers 3 to 8 to replace damaged piles;
- Fibre wrapping of damaged columns to limit concrete spalling and increase column strength;
- Beam-column joint retrofit using steel collars and fibre wrap;
- Transverse shear keys between girders at the top of capbeams;
- Deck joint repair;
- Beam seat extension at Pier 6; and
- Sidewalk grating, fence and roadway railing repair.

Figure 19 shows details of the permanent retrofit at a typical bent. The permanent retrofit was carried out during shutdown of the existing bridge between October 2006 and May 2007, while traffic was diverted to the new bridge to the west.

Open-toe steel pipe piles, 610 mm outside diameter by 12.7 mm wall thickness, driven to toe bearing in the dense till-like soils underlying the soft marine clay were used to replace the existing damaged concrete piles. Two new piles were installed at each existing column or pile cap at Piers 3 to 8. The pipe piles were driven to practical refusal (15 blows for last 25 m of penetration) using a Berminghammer B64 diesel hammer (see Fig. 20). Pile lengths varied from 43 m to 57 m. Selected piles were monitored with a Pile Driving Analyzer (PDA). CAPWAP analyses of PDA wave traces during pile re-strikes indicated fully mobilized capacities between 4300 kN and 5000 kN per pile. During pile driving, the bridge structure from Piers 2 to 9 was monitored. No measureable movements or excessive vibrations were recorded at the existing pile supported piers.

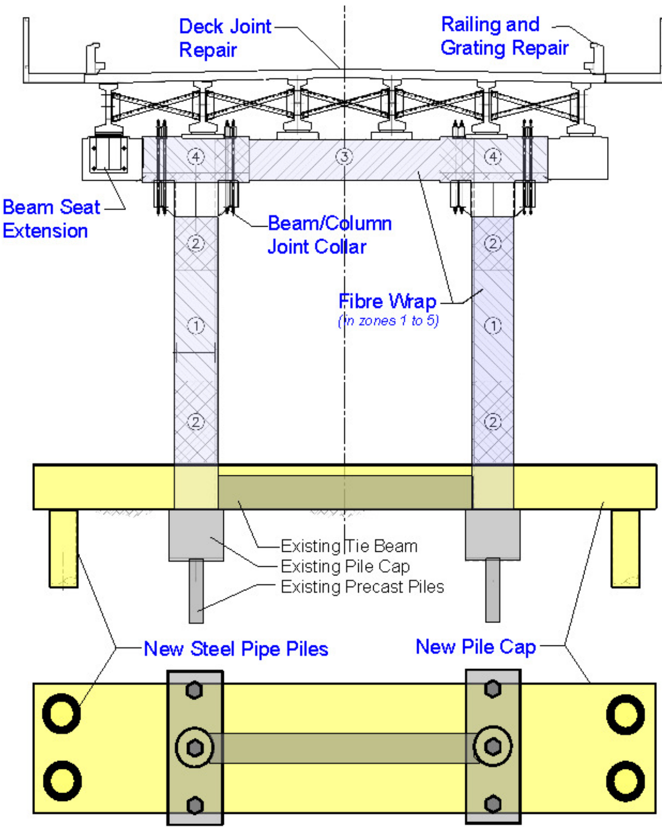

Figure 19 Permanent bridge retrofit including new pile caps and steel pipe piles

Figure 20. Installation of replacement steel pipe piles at east side of bridge

Figure 21 shows a typical bent after permanent retrofit. Note the new parallel overpass in the background.

Figure 21. Bent after permanent retrofit (looking west)

9 SUMMARY

The Roger Pierlet Overpass, built in 1975, was displaced and damaged in November 2004 by foundation soil movement caused by failure of a large soil stockpile placed adjacent to the bridge. The site is underlain by soft and compressible marine clay, up to 50 m deep, overlying very dense till-like deposits. The concrete bridge structure is supported on precast concrete piles toe bearing in the till-like soils. The soil failure resulted in cracking in pier columns, pile cap beams, and foundation piles (inspected at underside of pile caps). Shortly after the bridge damage was discovered, temporary support towers were erected to provide temporary support for the bridge decks and to allow traffic to safely continue on the bridge.

As part of the post-event ground investigations, cone penetration tests and vane shear tests were carried out in the vicinity of the displaced bridge piers. Inclinometers, piezometers and movement hubs were installed to monitor performance of the bridge and foundations. Subsequent permanent retrofit of the bridge included strengthening of columns and beam/column joints, extension of existing pile caps in the transverse direction, and addition of steel pipe piles to replace the damaged concrete piles.

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