Analysis of Seawall Concepts Using Yielding Soil Anchors

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ABSTRACT

Stretching 8,016 feet (2,443 meters) along downtown Seattle's waterfront, the 75-year-old Alaskan Way Seawall provides the interface between the city's downtown core and Elliott Bay. Damage to the seawall during the 2001 Nisqually earthquake led to investigations that confirmed the seawall is deteriorating and seismically vulnerable to potential liquefaction of the loose soils that underlie the structure. The City of Seattle is planning to replace the seawall. To further advance the proposed replacement program, two replacement concepts were developed. One used secant pile technology while the other used yielding soil anchors in combination with soil cement (jet grouting).

A soil-structure interaction program was used successfully to model the complex dynamic interaction between the soil, the existing seawall and timber relieving platform, and the structures proposed to replace the seawall. The structural and geotechnical engineers collaborated on the development of an innovative hybrid system in which the soil improvement or secant pile wall resists service loads and liquefied soil pressures while the yielding soil anchors resist the inertial effects of a seismic event.

This paper will review the development of the replacement alternatives analysis, the lessons learned, and the importance of successful structural-geotechnical collaboration in order to provide a solution to a complex soil-structure interaction problem.

INTRODUCTION

The Alaskan Way Seawall extends along the Seattle waterfront from Bay Street on the north to Washington Street on the south as shown in Figure 1. This paper is concerned with the 1934 seawall between Broad Street and Madison Street. The Type A wall (Figure 2), consists of a 40-foot-wide (12.2 meter) timber relieving platform which laterally supports a precast face panel supported on a 15-foot-high (4.6 meter) sheet pile wall. The Type B wall, (Figure 3), consists of a 60-foot-wide (18.3 meter) relieving platform supported on a sheet pile wall of varying height.

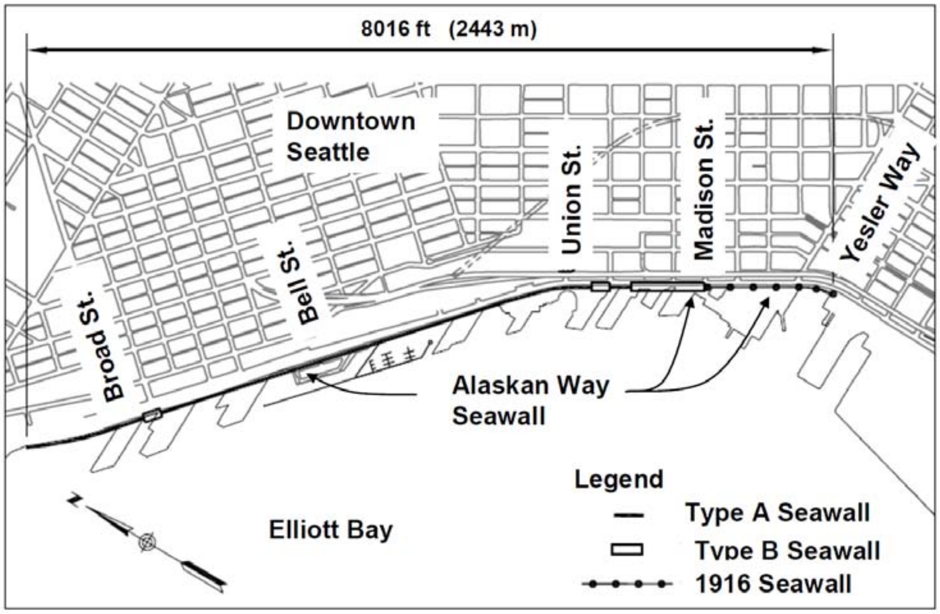

Figure 1. Plan of Seattle waterfront showing the Alaskan Way Seawall.

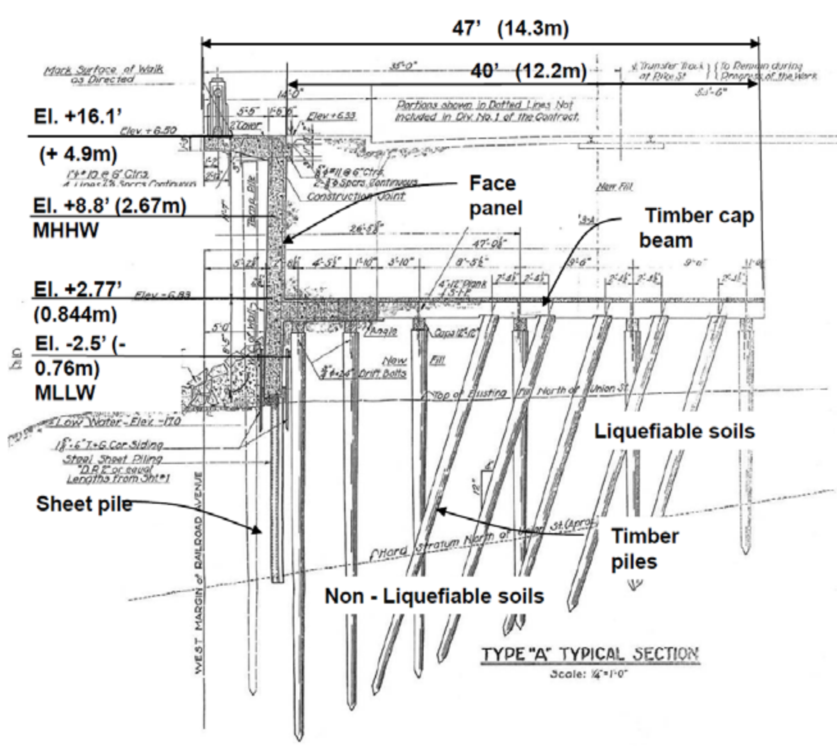

Figure 2. Type A seawall typical section.

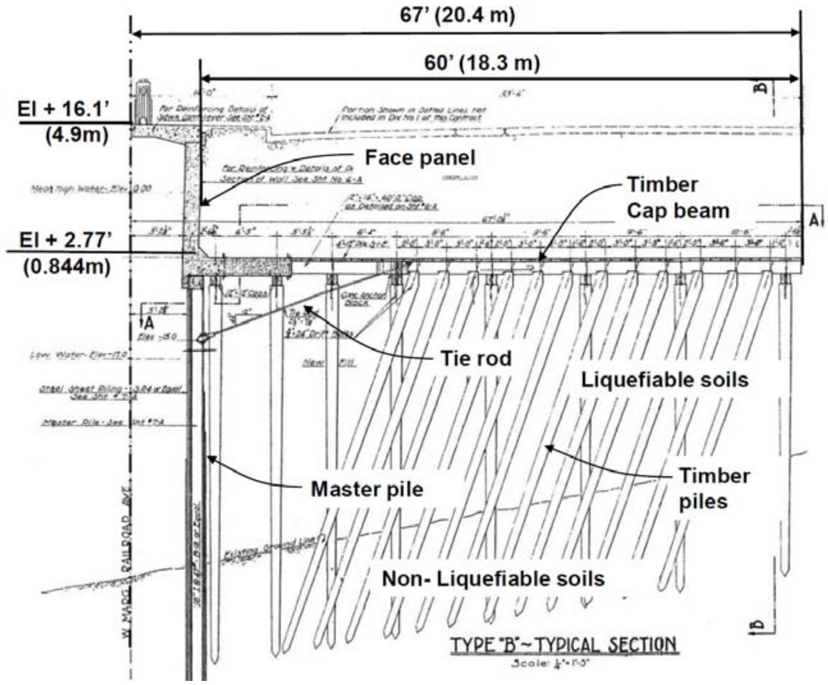

Figure 3. Type B seawall typical section.

Studies have determined that the seawall is seismically vulnerable due to liquefaction of the fill behind it; this liquefaction could result in large displacements of the wall and potentially in its complete failure (BergerABAM 2003 and Shannon & Wilson 2003). Because of this seismic vulnerability and the fact that both the seawall and the viaduct are reaching the end of their useful lives, the Washington State Department of Transportation, City of Seattle, and Federal Highway Administration conducted studies to replace the seawall (BergerABAM 2002, BergerABAM 2004). The studies culminated in the concept study that is the subject of this paper (PB, *BergerABAM, Shannon and Wilson* 2008). PB is the lead engineering consultant for the project, BergerABAM is the structural consultant for the seawall replacement, and Shannon & Wilson is the geotechnical consultant

SEISMIC DESIGN CRITERIA

The seismic design criteria used in the study are

- Expected Earthquake (EE) Type A and B Seawalls – Ground motions with an approximately 108-year return period
- Rare Earthquake (RE-2500) Type B Seawall – Ground motions with an approximately 2,500-year return period.
- Rare Earthquake (RE-1000) Type A Seawall – Ground motions with an approximately 1,000-year return period.

Figure 4 shows plots of acceleration, velocity, and displacement versus time for RE-2500.

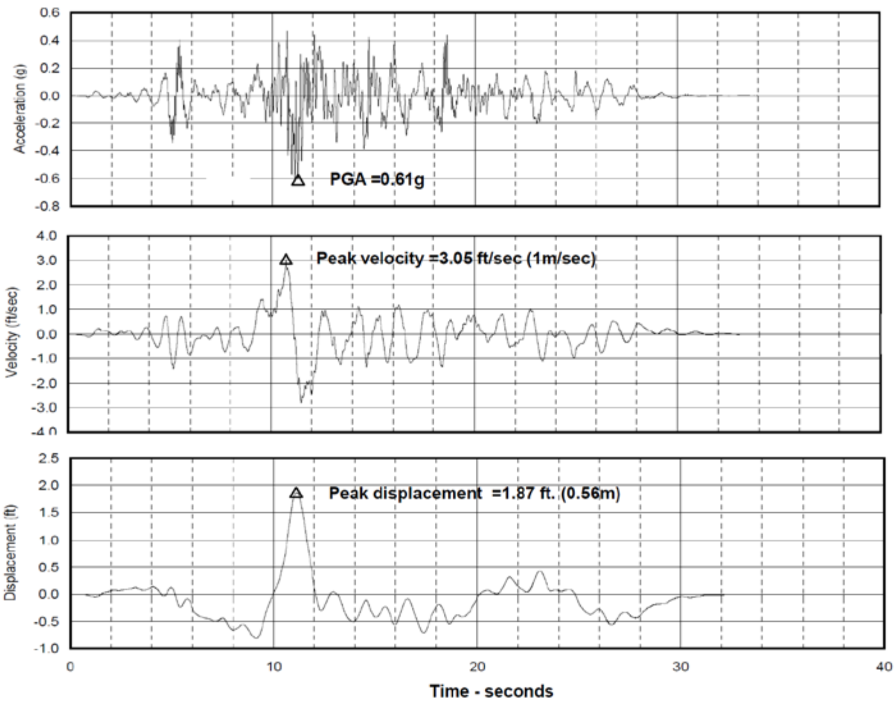

Figure 4. RE-2500 ground motions.

OVERVIEW OF CONCEPT DEVELOPMENT PROCESS

Prospective design concepts were developed and presented to the project team and modified based on the feedback received. Preliminary analyses were then performed for these concepts using the software L-Pile® (Reese and Wang, 2006) with static soil pressures and soil parameters developed by the team. The concepts were screened using an evaluation matrix and reduced to two preferred design concepts as shown in Figure 5. One used secant pile technology for the Type A wall, and the other used soil improvement technology (jet grouting) for the Type B wall. The preferred design concepts were analyzed as follows.

Dynamic soil-structure interaction (DSSI) analyses were performed for each preferred concept using the software program Fast Lagrangian Analysis of Continua (FLAC, Itasca Consulting Group, 2005). FLAC uses a finite difference method to model soil or rock and finite element beams, piles, and cables to model structures. FLAC's dynamic modeling capabilities were used to simulate earthquake loading. Potential liquefaction of the soils beneath and behind the seawalls was modeled using the UBCSAND constitutive equations developed at the University of British Columbia (Byrne et al., 1995; Puebla et al., 1997; Beaty & Byrne, 1998; and Byrne et al., 2004). Hydrodynamic effects were not modeled in the DSSI analyses.

TYPE A SECANT PILE CONCEPT DEVELOPMENT

A cantilever secant pile wall was selected as the first concept to be analyzed using FLAC. The wall consisted of 8.2-foot-diameter (2.5 meter) drilled shafts at 7.5 feet (2.3 meter) on-center with 1.4 percent reinforcement in all shafts. The nominal moment capacity of the wall is approximately 22,000 kip-ft (29,000 kN-m) per shaft.

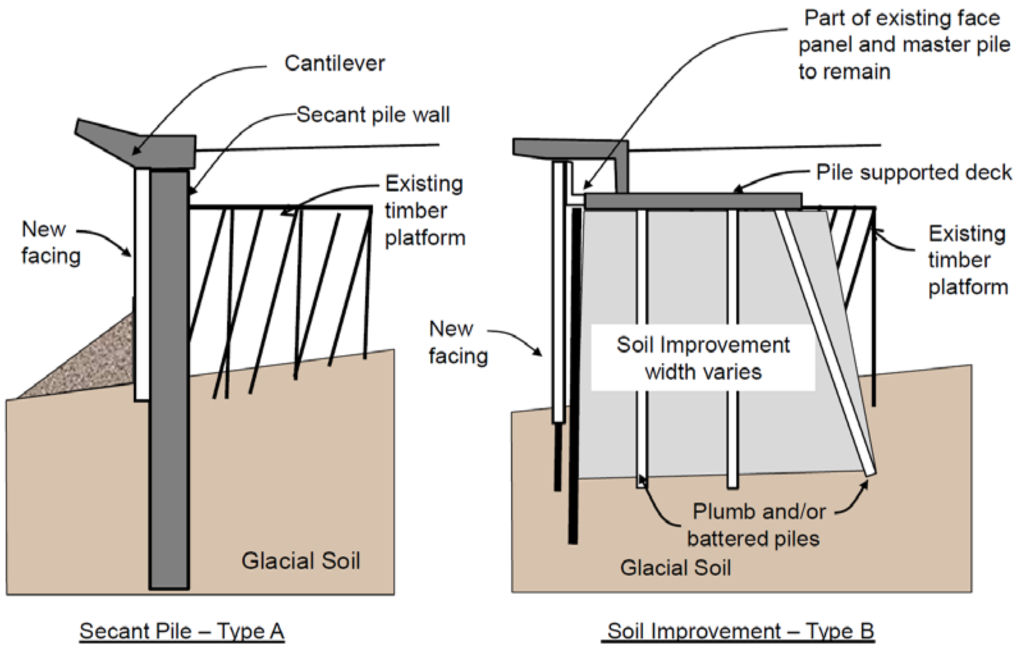

Figure 5. Initial concepts studied.

The structural and geotechnical engineers collaborated on the development of a FLAC model of the seawall that included the timber relieving platform. Initial FLAC runs were performed using static loads to validate the model. The results were reviewed and the mesh and structural components were adjusted as needed until the team gained confidence in the numerical model. The findings from the FLAC analyses were then presented jointly by the geotechnical and structural engineers at team meetings. Based on the feedback from the team, the concept was modified and further FLAC analyses were conducted as needed.

Eleven variations of the secant pile concept were studied, varying the ground motion input and secant pile stiffness and embedment, with and without the existing timber platform. A summary of the results follows.

- The secant pile response computed for the RE-1000 ground motions was observed to be dominated by the ground-velocity pulse, i.e., near-fault effects.
- The relieving platform has a minimal effect on the secant pile wall. Results indicate the inertial effects on the liquefied soil restrained by the robust secant pile wall causes the platform to lift off the piles resulting in heaving of the street behind the wall.
- The peak moment which includes the effects of both the inertia forces and the liquefaction pressure was approximately 25,000 kip-ft (33,900 kN-m) per shaft which yields the shaft reinforcement.
- The moment in the shaft at the end of shaking (deemed to be due solely to liquefied soil) was 10,000 kip-ft (13,600 kN-m) per shaft, or about 40 percent of the peak moment. The permanent shaft displacement at the end of shaking considering yielding was calculated to be about 7 inches.
- The point of maximum moment was about 8 feet (2.4 meters) below the top of the dense glacial soils, and was insensitive to the wall stiffness and the loading.

TYPE B SOIL IMPROVEMENT CONCEPT DEVELOPMENT

Development of the Type B concept proceeded after the team developed confidence during modeling of the relatively simple Type A wall. The initial Type B concept used soil improvement (jet grout) with additional structural support consisting of a pipe pile-supported, reinforced concrete seawall and slab, with H-pile-supported face panels shown conceptually in Figure 5. The pipe pile farthest from the seawall serves as a tie-down member to resist overturning forces on the jet grout block. To evaluate the effect of the tie-down member, analyses were made with no tie-down, a short vertical tie-down, a long vertical tie-down, and a long battered tie-down. Initially, three widths of jet grout were considered: 22 feet (6.7 meters) wide at the top and 32 feet (9.8 meters) wide at the bottom, 29 feet (8.8 meters) wide at the top and 48 feet (14.6 meters) wide at the bottom, and 32 feet (9.8 meters) wide at the top and 70 feet (21.4 meters) wide at the bottom.

Three improved soil shear strengths were considered.

- Low strength improved soil in which the shear strength represents the case where just enough jet grout has been added to the improved soil to limit shear strains in the soil to a level below which liquefaction does not occur, corresponding to an approximate area replacement ratio of about 0.3.
- 50 percent column coverage which represents alternating rows of jet grout and fill/native soils oriented parallel to the wall face.
- 50 percent composite coverage which represents alternating rows of jet grout and fill/native soils oriented perpendicular to the wall face, judged by the geotechnical team to be more representative of the jet grout placement program that would be used for seawall replacement.

As with the Type A wall, an iterative analysis procedure was used to develop the preferred design concept for the Type B wall. Fourteen preliminary models were run varying the strength, width, and density of the jet grout and the configuration of the piles under the platform. A summary of the preliminary FLAC analyses follows:

- Horizontal wall displacements are large and insensitive to the width of the soil improvement if low strength improved soil is used. With 50 percent coverage, increasing the width of the soil-cement block substantially reduced displacements.
- Vertical tie-down piles were ineffective in reducing displacements for low-strength soil-cement but were somewhat effective for 50 percent jet grout coverage. Battered tie-down piles were found to be an efficient way of limiting displacements for 50 percent jet grout coverage.
- Under high inertial forces, the tensile force demand computed for stiff tie-down piles was observed to exceed the geotechnical uplift capacity of the piles. Consequently, battered soil anchors with a yielding zone were introduced to limit the tensile demand on the anchors.

CONSTRUCTABILITY WORKSHOP

Based on the findings from the initial analysis, the concepts were further developed by a panel of design and construction experts during a three-day constructability workshop. A significant outcome of the workshop was the development of two solutions that used yielding anchors for both the Type A and Type B walls as follows.

- Braced secant pile concept (BSP)
- Anchored soil improvement concept (ASI)

FINAL CONCEPT ANALYSIS AND RESULTS

After the constructability workshop, 16 additional FLAC analyses were performed and the yielding anchor concepts were further refined. The yielding anchor concept is illustrated in Figure 6 for the BSP concept and Figure 7 for the ASI concept. Table 1 shows a summary of the results.

Table 1. Summary of Lateral Seismic Displacements (∆)

Wall Type	Earthquake	Peak ∆ (inches, mm)	Final ∆ (inches, mm)
Type A – BSP	RE-1000	5 (127)	1 (25)
Type A – ASI	RE-1000	8 (203)	8 (203)
Type B – BSP	RE-2500	12 (305)	9 (229)
Type B – ASI	RE-2500	4 (102)	3 (76)

SELECTION OF PREFERRED CONCEPTS

All of the concepts shown in Table 1 were judged by the team to have acceptable performance and cost estimates were developed for each. Cost estimates were performed using a high unit cost and a low unit cost for both the jet grout and secant pile wall because the numbers of contractors able to complete jet grouting and drilled shaft work are limited. The concepts were then compared using cost and other subjective criteria.

The results indicated that, for the Type B wall, the ASI concept was clearly more economical, while both of the concepts appeared to be cost competitive for the Type A wall. Therefore, two alternatives were selected to be carried forward into preliminary design as shown in Table 2. Alternative 1 is shown in Figure 8. Alternative 2 is not shown, but uses ASI for the Type A wall similar to that shown for Type B.

Table 2. Recommended Design Concepts

Location	Alternative-1	Alternative-2
Type A Wall	BSP	ASI
Type B Wall	ASI	ASI

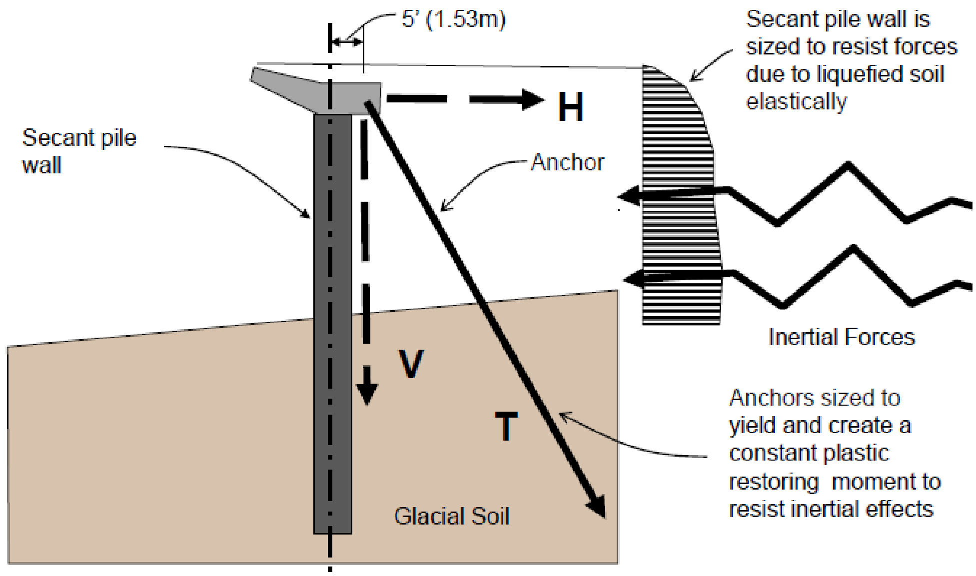

Figure 6. The yielding anchor concept illustrated for the braced secant pile.

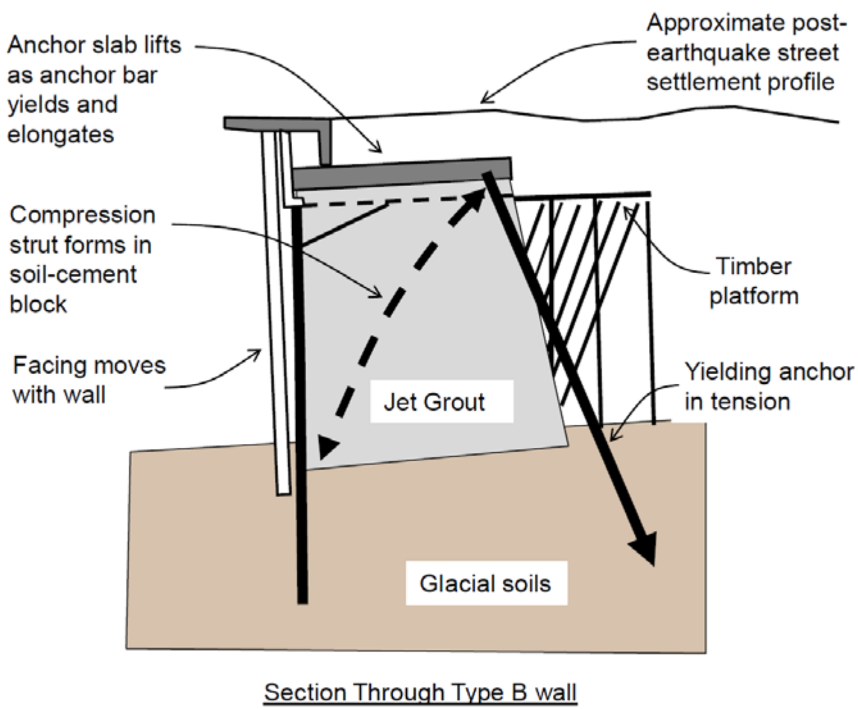

Figure 7. The yielding anchor concept illustrated for the anchored soil improvement.

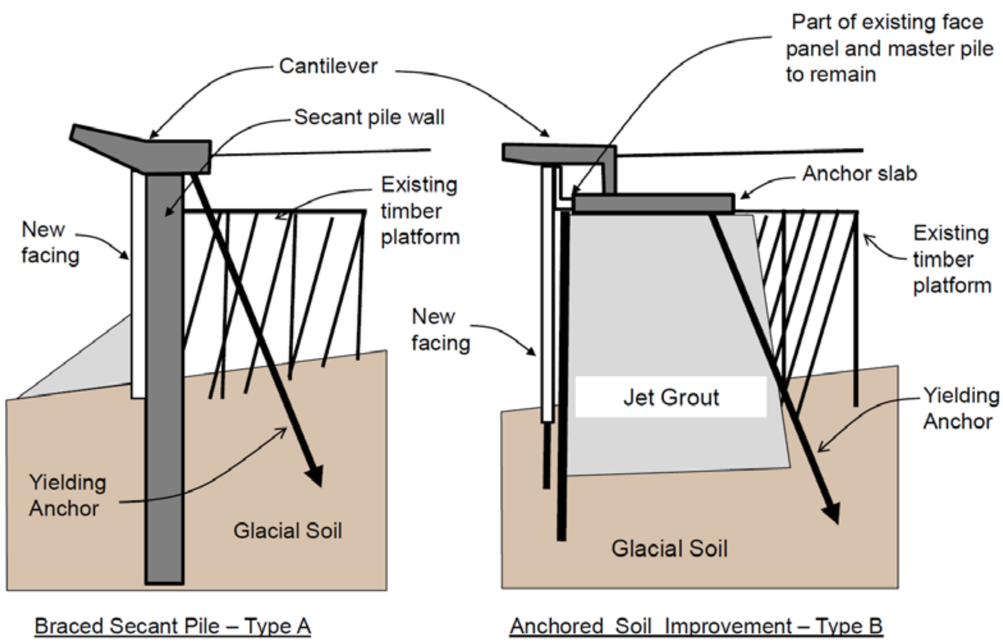

Figure 8. Final concepts.

LESSONS LEARNED

Following are some of the key lessons learned by the design team.

1. FLAC is a useful tool for modeling complex problems in soil structure interaction. However, when FLAC is used for structural analysis, the traditional roles of the structural and geotechnical engineer may become blurred. Having continuous dialogue between the structural and geotechnical engineers is important.
2. Performing static FLAC analysis on the existing Type A seawall was a useful process as it allowed the team to gain confidence before it began the time-consuming dynamic analysis.
3. Performing the initial dynamic FLAC analysis on the simple Type A cantilevered secant pile wall using varying shaft length and stiffness allowed the team to understand the complex soil structure interaction better, separate the inertial effects from liquefaction, and evaluate alternate concepts using simple hand calculations.
4. The team's approach—having the geotechnical engineer provide the FLAC analysis to the structural engineer, who then performed independent QC on the results and presented the results to the team—was very effective.
5. It is important to present the results of the FLAC analysis to the design team in several different formats. Tables, deflected shapes, moment and shear diagrams, stress contour plots, and the like can convey the complex soil-structure interaction effectively to the team and the client.

SUMMARY AND CONCLUSION

DSSI analyses were successfully used to model the complex dynamic interaction between the soil, the existing seawall and timber relieving platform, and the proposed seawall replacement structures. Through close collaboration between the structural and geotechnical engineers, an innovative hybrid system was developed in which the soil improvement or secant pile wall resists service loads and liquefied soil pressures while the yielding soil anchors resist the inertial effects of a seismic event.

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