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SYNOPSIS The performance of several temporary deep shored earth retaining systems during the January 17, 1994 Northridge earthquake in Southern California is documented. These shoring systems ranged from 30 to 70 feet in depth and were subjected to severe ground motions with little deflection or distress.

INTRODUCTION

The Northridge earthquake of January 17, 1994 in Southern California provided a severe testing of deep shored earth retaining systems. At the time of the magnitude 6.7 (moment magnitude) earthquake, there were several on-going construction projects with substantial excavations using temporary shoring systems consisting of soldier beams and tied-back anchors. These excavations ranged from 30 to 70 feet in depth. There was also a project where construction had been temporarily suspended with a shoring system retaining an embankment of about 30 to 40 feet. All of these shored earth retention systems experienced significant strong ground motions.

TIED-BACK SHORING SYSTEM DESIGN PRACTICE IN SOUTHERN CALIFORNIA

Tied-back shoring systems as a means of temporary deep excavation support have been widely used in Southern California since the 1960's, especially since they provide an unobstructed work area within the excavation (Maljian and Van Beveren, 1974). In Southern California, it is common practice to use tied-back shoring for excavations greater than 15 or 20 feet in depth where slope cuts would not be permissible and where the use of cantilevered shoring is not practical. In practice, steel soldier beams are inserted into drilled holes which are backfilled with structural or lean-mix concrete. To resist the lateral earth pressures and any surcharge pressures, the passive resistance of the toe of the soldier piles and the horizontal resistance of the tied-back anchors are used. Generally, the drilled tied-back anchors are friction anchors installed at various depths as the excavation advances until the full depth of the excavation is reached. The use of drilled and belled anchors is rarely used. Lagging may be installed between the soldier beams which may be spaced at 6 to 8 feet on centers.

For design of the restrained or tied-back shoring, it is common practice to assume a trapezoidal distribution of earth pressure. A typical recommended pressure distribution, where the surface of the retained earth is level, is illustrated in Figure 1. The maximum pressure for normally consolidated soils is typically on the order of 19H to 20H in units of pounds per square foot, where H is the height of the shoring in feet. It is not common practice to include a seismic earth pressure in the design of temporary retention systems.

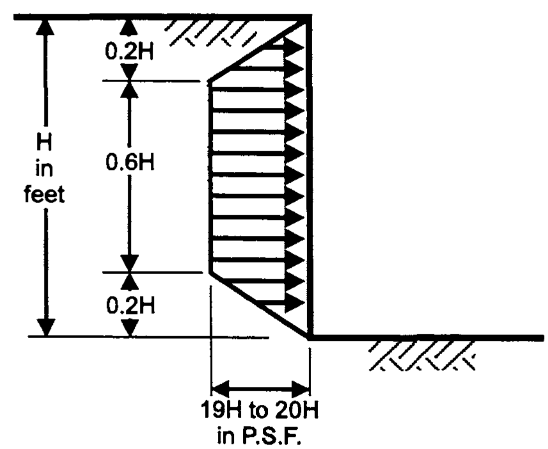

Figure 1 Typical Trapezoidal Distribution of Earth Pressure for Tied-Back Shoring Systems

The frictional resistance of the tied-back anchors is determined by the geotechnical consultant. The frictional resistance is generally assumed to be present behind the active wedge adjacent to the shoring. The active wedge is defined by a plane drawn at 30 to 35 degrees from vertical through the bottom of the excavation. The frictional resistance of the anchors within the assumed active wedge is ignored. The anchors are typically installed at angles of 15 to 30 degrees below horizontal. Steel rods or strands are installed in the anchor holes which are filled with concrete placed by pumping from the tip out, and the concrete is to extend from the tip of the anchor to the active wedge. To minimize the chances of caving within the active wedge, it is normal to fill that portion of the anchor with sand or sand-slurry.

After the initial tied-back anchors are installed, it is common practice to determine or verify the capacities of the anchors by testing. A few of the initial anchors are selected by the geotechnical engineer and these anchors are tested to 200 percent of the design load for a period of 24 hours to verify the estimated design capacity. The loads are applied incrementally to the anchors in eight equal increments of load until the 200 percent load is achieved. During the load test, the deflection is measured. The criteria for a successful test may be that the total deflection during the 200 percent load not exceed 12 inches, and that the anchor deflection not exceed 0.75 inch in the 24 hours after the 200 percent load is applied.

The remainder of the tied-back anchors are pretested to at least 150 percent of the design load. The total deflection during the tests should not exceed 12 inches and the rate of creep not exceed 0.1 inch over a 15-minute period for a test to deemed satisfactory. After a satisfactory test, each anchor is locked-off at the design load. Frequently, the locked-off load is verified by rechecking the load in the anchor; if the locked-off load varies by more than 10 percent from the design load, the anchor is reset.

TIED-BACK SHORING SYSTEMS SHAKEN BY THE NORTHRIDGE EARTHQUAKE

The performance of some four temporary tied-back shoring systems in the Los Angeles area were studied. The four projects are identified as:

Site No.	Location
1	Union Station Gateway-Downtown L.A.
2	Walt Disney Concert Hall-Downtown L.A.
3	Ocean Hotel-Santa Monica
4	Site west of Downtown L.A.

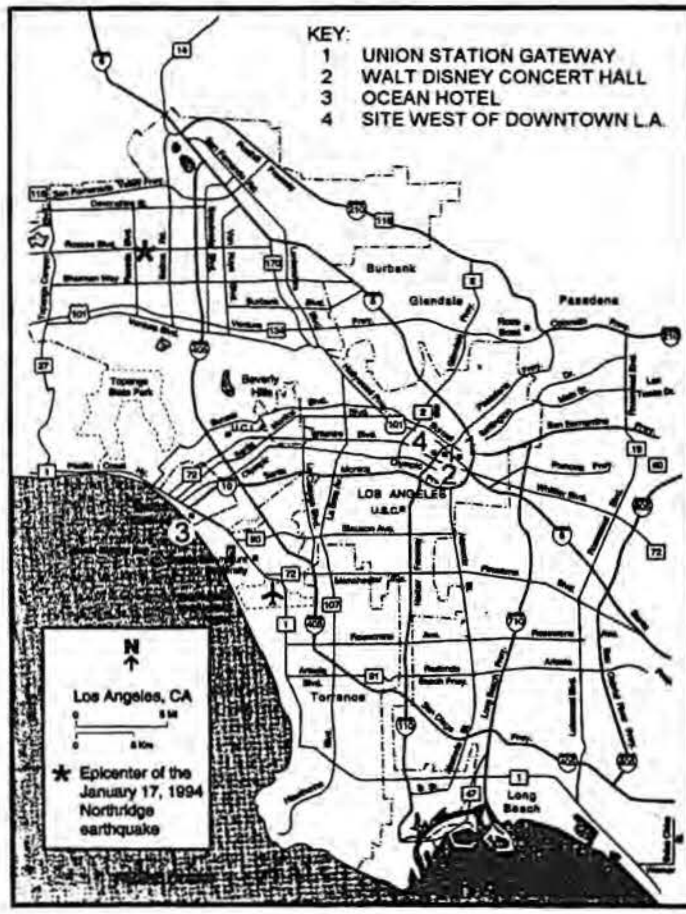

Figure 2 Location of Four Sites with Temporary Tied-Back Shoring Systems (After Housner 1994)

Site Nos. 1 and 2 were active construction sites at the time of the earthquake. The shoring at Site No. 3 was installed in 1990 and construction has been slowly proceeding since that date with foundations and some lower basement walls having been constructed. Construction at Site No. 4 had ceased in about 1983 and has been dormant since that date. The locations of the four project sites are shown in Figure 2.

Union Station Gateway Site

This site is located northeast of downtown Los Angeles and is immediately east of the Union Station transportation center. The site is generally level. This project consists of construction of several high-rise buildings over a common four level subterranean structure. The excavation is approximately 360 by 760 feet in plan and is 35 to 52 feet in depth; about 2,000 lineal feet of shoring consisting of 238 soldier piles was installed. Shoring for the subterranean construction was installed in the spring and summer of 1993.

The soils at the site consist of about 90 to 110 feet of Quaternary age alluvial deposits underlain by siltstone bedrock. The alluvial deposits are generally medium dense to dense silty sands and sands with few layers of sandy silt and are abundant in gravel and cobbles. The siltstone is a soft rock common to this area of Los Angeles and is very stiff. Ground water levels were measured in the exploratory borings at a depth of about 30 feet. approximately 5 feet above the lowest level of the excavation. The site was dewatered to allow for the subterranean construction and the installation of the drilled soldier piles.

The soldier piles consisted of 14-inch wide flange steel beams encased in 3,000 p.s.i. concrete below the bottom of the excavation and encased in a 1-1/2 sack per cubic yard sand-cement slurry above the bottom of the excavation. The shoring was typically retained by two to three rows of tie-back anchors attached at several points below the top of each soldier pile. A typical cross section of the shoring is shown in Figure 3.

At the time of the earthquake, the shoring was completed and the subterranean parking structure was under construction. Most of the shoring was still retaining the full height of the excavation at that time. A photograph of the shoring shortly after the earthquake is shown in Figure 4.

A free-field strong motion recording station operated and maintained by the California Strong Motion Instrumentation Program (CSMIP) is located about 1 mile west of the Union

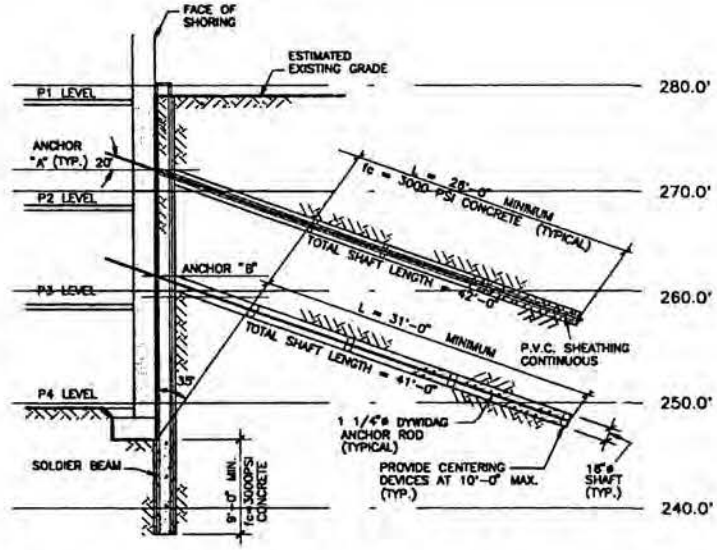

Figure 3 Typical Cross Section of Shoring, Union Station Gateway Site

Figure 4 Union Station Gateway Construction Site Shoring

Station Gateway site. The acceleration-time histories from the CSMIP recording station are shown in Figure 5. The peak ground accelerations were 0.13g in the east-west direction, 0.19g in the north-south direction, and 0.10g in the vertical direction (Shakal et al., 1994). However, the recording station site is on siltstone bedrock. Because of the alluvium beneath the site, we believe that the free-field ground motions at the Union Station Gateway were greater than those recorded at the CSMIP recording station.

Monthly survey monitoring of the tops of the soldier piles had been performed during the construction of the project. One set of survey readings was made on January 10, 1994, and another set of readings was made on January 18, 1994 to determine if there were any significant deflections or movement of the soldier piles. The surveyor's readings indicate that there was little horizontal movement of the tops of the soldier piles. Visual observations of the shoring did not indicate any obvious movements along the lengths of the soldier piles from the top to the bottom of the excavation. Some 47 out of the 230 installed soldier piles showed 0.01 to 0.02 feet (1/8 to 1/4 inch) of movement into the excavation; while five soldier piles had horizontal movements of 0.03 to 0.04 feet (3/8 to 1/2 inch) into the excavation. However, in the latter cases, the cumulative movement of the soldier piles was zero since the soldier piles were pulled into the retained embankment during anchor testing. The remaining soldier piles showed either no horizontal movement or up to 0.03 feet of movement into the shoring away from the excavation. Vertical measurements of the top of the soldier piles indicated that about two-thirds of the piles had a relative upward movement between 0.01 feet (about 1/8 inch) and 0.02 feet (about 1/4 inch). We speculate that this relative pile movement upwards may be due to seismic settlement of the underlying alluvial soils in the area of the surveyor's benchmark due to the strong ground shaking.

Considering the depth of shoring was on the order of 35 to 52 feet, horizontal deflections of 0.02 to 0.08 percent are well within the tolerable limits for shoring.

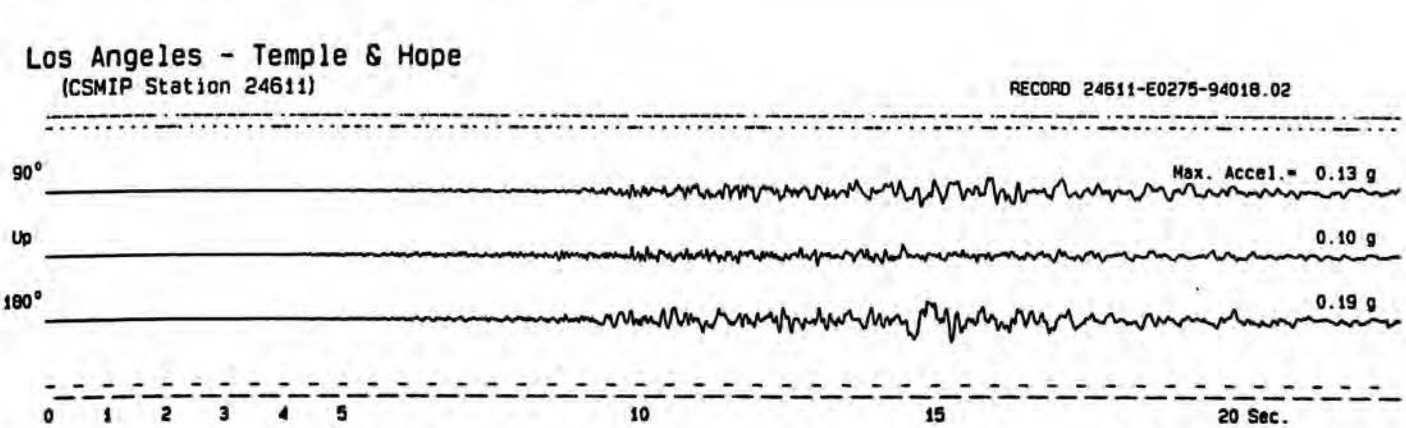

Figure 5 CSMIP Acceleration-Time Histories at Temple and Hope Station Free-Field Station (After Shakal et al., 1994)

Site 2- Walt Disney Concert Hall Site

This site is located in Downtown Los Angeles and is about 1 mile away from Site 1 (see Figure 2). The excavation is approximately 320 by 460 feet in plan and the shoring depth is typically about 50 to 70 feet. The subsurface conditions at the site mainly consist of interbedded sedimentary siltstone and sandstone bedrock. The bedrock presented adverse bedding for south-facing walls of the excavation and the shoring system had to be designed for higher than normal lateral earth pressures.

The shoring system consisted of drilled soldier piles retained by up to 6 rows of tie-back anchors. A total of 236 piles were installed for this project. A typical cross section of the shoring is shown in Figure 6. On January 17, 1994, some of the lower levels of the subterranean parking structure had been completed; however, the shoring still retained most of the height of the excavation. A photograph of the shoring shortly after the earthquake is shown in Figure 7.

This site is less than 1,000 feet from the CSMIP recording station at Temple and Hope Streets and the site conditions are very similar. The ground motions at the Concert Hall site would therefore be expected to be very similar to those at the recording station, as shown in Figure 5.

Monitoring of the shoring system began in March 1993 with one set of readings taken on January 14, 1994 and the following set on January 18, 1994. Based on a review of the surveyor's readings, 51 of the 236 piles showed horizontal movements of 0.01 foot (1/8 inch) into the excavation while the remaining piles did not exhibit any horizontal movements. Measurements at the top of the soldier piles indicated that they were on the order of 0.01 feet (1/8 inch) higher than the grade at the surveyor's benchmark.

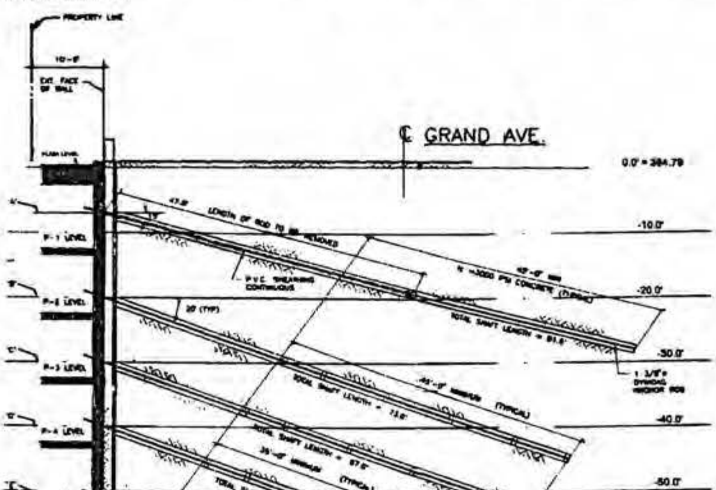

Figure 6 Typical Cross Section of Shoring, Walt Disney Concert Hall Site

Figure 7 Walt Disney Concert Hall Construction Site Shoring

Ocean Hotel Site

The site is located in Santa Monica and is near the Pacific Ocean. The site located on a west-facing bluff with a difference in elevation of about 30 feet from the top to the bottom of the bluff. The site measures about 190 feet from north to south and about 300 feet from east to west. The eastern and western sides of the site are bounded by public streets; to the south are one- and two-story residential buildings; to the north is a 5-story hotel with 3 levels of subterranean construction which extends about 30 feet below the highest grade on the bluff; this existing hotel was constructed in the late 1980s.

The soils at the site consist of Pleistocene age alluvial deposits. These deposits contain moderately stiff to stiff silty clays and clayey silts with dense silty sands and lesser amounts of sand, clayey sand and gravel. The water levels measured in the exploratory borings were higher on the east than on the west, perhaps indicating a sloping gradient towards the Pacific Ocean or the presence of perched water on top of some of the impermeable soil layers. The water level was measured at a depth of 32 feet below the ground surface at the higher eastern part of the site while water was measured at depths of 5 to 16 feet below the ground surface below the grade on the lower western part of the site.

Tied-back shoring was installed along the east and south sides of the site for the building excavation; a short section along the north side was shored near the northeast corner. Shoring was not needed along most of the north side since the adjacent hotel's subterranean structure extended to about the same elevation as the proposed construction. Along the north side, the excavation exposed the shoring that was installed for the adjacent hotel project. The shoring is essentially cantilevered from its foundations; the existing shoring, however, has no functional purpose as it does not support the existing hotel building.

Shoring was not needed along the west side as the lower level will essentially bottom out at the lower street elevation. There are a total of 4 soldier piles along the north side, 33 soldier piles along the east side, and 50 soldier piles along the south wall.

The shoring system for most of the site was about 35 feet in height, and consisted of 16-inch wide flange steel soldier beams encased in 3,000 p.s.i. concrete below the excavated level and encased in a 1-1/2 sack per cubic yard sand-cement slurry above the excavated level. A single tie-back anchor was attached at a point about 10 feet below the top of each soldier beam and installed at an angle of 20 degrees below horizontal. A typical cross section of the shoring is shown in Figure 8. A photograph of the shoring is shown in Figure 9.

A free-field strong motion recording station operated by CSMIP is located at the Santa Monica City Hall grounds, less than two blocks east of the Ocean Hotel construction site. The acceleration-time histories from the City Hall grounds are shown in Figure 10; the peak ground accelerations were 866 cm/sec/sec (0.88g) in the east-west direction, 362 cm/sec/sec (0.37g) in the north-south direction, and 228 cm/sec/sec (0.23g) in the vertical direction (Darragh et al., 1994). The east-west ground motions were very vigorous and there was extensive damage in the City of Santa Monica.

Monthly survey monitoring of the tops of the soldier piles had been performed during the construction of the project. One set of survey readings was made on January 14, 1994, just 3 days prior to the earthquake. Another set of readings was commissioned on January 20, 1994 to determine if there were any significant deflections or movement of the soldier piles. Visual observations of the shoring do not indicate any obvious movements along the lengths of the soldier piles from the top to the bottom of the excavation. The northern soldier piles did not exhibit any horizontal movements. Along the east wall, 12 of the 33 soldier piles have measurements that indicated that the top of the piles moved out towards the excavation by an amount of 0.01 feet (about 1/8 inch) in the period from January 14 to 20; three soldier

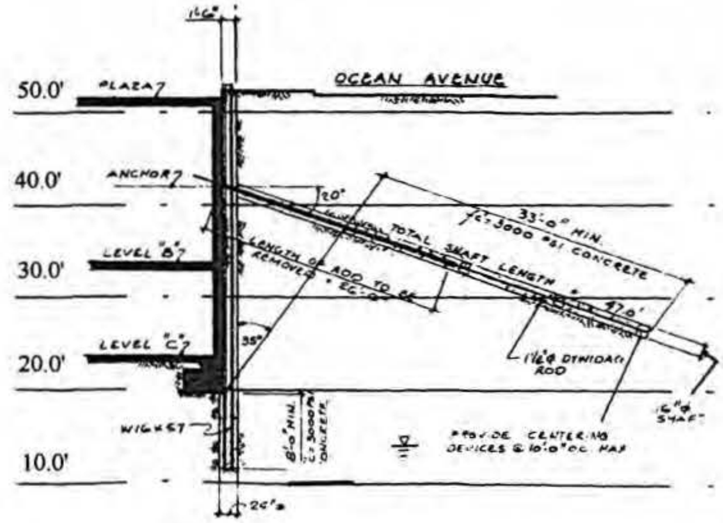

Figure 8 Typical Cross Section of Shoring, Ocean Hotel Site

Figure 9 Ocean Hotel Construction Site Shoring

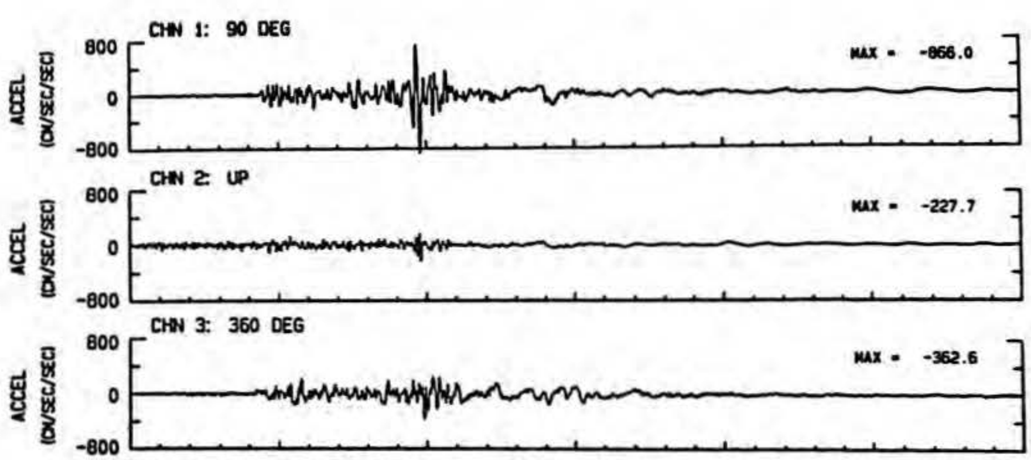

Figure 10 CSMIP Acceleration-Time Histories at Santa Monica City Hall Free Field Station (After Darragh et al., 1994)

piles showed movements of 0.01 feet into the retained embankment. Along the south wall of the shoring, two soldier piles had readings that showed 0.01 feet of movement towards the excavation and one soldier pile had readings indicating 0.02 feet (about 1/4 inch) towards the excavation. 8 soldier piles showed horizontal movement away from the excavation; 7 of the 8 indicated 0.01 feet of movement, and the other showed 0.02 feet of movement toward the retained soil. It was interesting to note that the vertical measurements of the top of the soldier piles indicated that almost all of the surveyed piles had a relative movement upwards between 0.01 feet (about 1/8 inch) and 0.03 feet (about 3/8 inch) with respect to the benchmark. We speculate that this relative pile movement upwards may be due to seismic settlement occurring in the area of the benchmark due to the strong ground shaking.

Site West of Downtown Los Angeles

In 1983, a temporary tied-back shoring system was installed at a site west of the downtown section of Los Angeles for a major high-rise building project to be built in two phases. The shoring system was installed for both phases of the project, however, only a mid-rise structure was constructed in the first phase and just a portion of the second phase's subterranean structure was constructed, leaving an estimated 30 to 40 foot height of the shoring system to support the embankment since construction ceased about 11 years earlier; see Figure 11.

Figure 11 Construction Site West of Downtown Los Angeles

This site is about one-half mile west-southwest from the CSMIP recording station at Temple and Hope Streets; the ground motions at the site are believed to have been similar to those at the recording station. Visual observations of the retained areas behind the shoring system several months after the Northridge earthquake did not show any obvious signs of significant movement of the soldier piles. Ground cracks behind the shoring system were not evident.

CONCLUSIONS

The tied-back shoring systems in the Los Angeles area experienced significant ground motions during the Northridge earthquake. Although the shoring sites were not in the areas where the ground motions were the strongest, the sites in the Downtown Los Angeles area were subjected to horizontal ground motions with accelerations on the order of 0.2g for a duration of at least 10 seconds. The site in Santa Monica may have experienced a peak ground acceleration of almost 0.9g in the east-west direction, with sustained ground accelerations of about 0.4g for about 10 seconds. The survey data taken after the earthquake indicates very nominal displacements with no failures, even though the shoring systems were designed only for static earth pressures and did not account for seismic earth pressures.

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