ABSTRACT: The MUNI turnback project included the extension of the MUNI rail lines in tunnels that run above and close to BART subway tunnels near San Francisco Bay. The MUNI tunnels were excavated in soft soils using shield tunneling and open-face mining methods under compressed air to minimize ground disturbance. An extensive monitoring program was implemented to monitor and safeguard the BART tunnels continually during MUNI tunnel construction. The BART tunnel deformations were less than 12 mm, within pre-construction predicted deformations.

RESUME: L'ouvrage-MUNI turnback project-incluait l'extension des lignes ferroviaires de MUNI aux tunnels ferroviaires, au-dessus et proches du Metro BART, à côté de la baie de San Francisco. La réalisation des tunnels de MUNI été achevée dans des terres fines, en utilisant les méthodes du bouclier perceur et minière à front ouvert par la méthode à l'air comprimé, pour minimiser le dérangement du terrain. Un dispositif extensif de surveillance à été mise en œuvre durant l'exécution pour s'assurer, du cote étanchéité du Metro BART. Les déformations mesurées étaient moins de 12 mm, nettement inférieur aux déformations prévues.

1 INTRODUCTION

The Bay Area Rapid Transit (BART) system is a commuter rail that is used daily by thousands of riders to commute from the East Bay to San Francisco. Along Market Street in San Francisco, MUNI Metro (local light rail system) twin tunnels run parallel to and above the BART twin tunnels. The tunnels were built in the early 1970’s (Figure 1).

The MUNI Metro Turnback (MMT) project is an extension of the existing San Francisco MUNI Metro subway under Market Street. The purpose of the project is to provide a more efficient turnback track configuration and bring the track to ground surface to connect with the planned extension of the MUNI Metro to Mission Bay. The construction of the MMT included twin tunnels that were mined just above the existing BART tunnels. The new tunnels run parallel to and above BART Tunnels for about 150 m with a vertical separation distance ranging between 1.2 m and 5 m.

2 PRE-CONSTRUCTION CONDITIONS

The BART tunnels lie in recent soft San Francisco Bay Mud deposits. The Bay Mud is overlain by a 4.5-10m thick layer of miscellaneous fill consisting mainly of dune sand. Ground water is at a depth of 1.5 to 3.0 m below ground surface. Figure 1 shows the geologic profile of the site. The Bay Mud is a marine soft to stiff plastic clay deposit. The upper portion contains varying amounts of sand, while the lower portion is relatively free of sand. The clay is normally consolidated in the upper portion, and slightly overconsolidated in the lower portion. The thickness of the Bay Mud increases toward the Bay from about 18 m near the Spear Street Shaft to about 27 m or more east of Steuart Street. The Bay Mud has a natural water content of 48-81 %, a plasticity index PI=22-60%. The Bay Mud at the site has an undrained shear strength ranging between 24 kPa at the top of the deposit and increasing to 72 kPa at a depth of 30 m corresponding to $S_u/\sigma'_v=0.28-0.34$. The initial modulus ratio, $E/\sigma'_v$, ranges between 110 and 300.

The BART tunnels are lined with a bolted segmental steel liner. The segment joints are gasketed and caulked with lead to prevent water seepage into the tunnel. During BART tunnel construction, in the 1960’s, tunnel excavation encountered nearly 200 abandoned timber piles. The timber piles were foundations for waterfront facilities that existed around the turn of the century along Market street. These piles were cut to just above the BART tunnel crown before installing steel liner segments. Dents developed in the steel liner at the locations of a few of the piles, possibly due to the down drag on the piles and consequent point loading of the liner. Steel plates were welded at weak areas to reinforce the lining.

3 DESIGN ANALYSIS AND MOVEMENT PREDICTION

The construction of MUNI tunnels close to BART tunnels exposed the BART tunnels to deformations that could have affected train operations and tunnel liner. Extensive studies were carried out to study the potential impact on BART tunnels. Analyses were conducted using closed-form solutions as well as the finite element method to calculate the stresses in the steel liner (Birkmyer 1987) and soil deformations due to MUNI excavations (Interpacific Technology, Inc. 1991). The FE analysis included models of the soil and the liner. The fill and the Bay Mud were modeled using
hyperbolic stress-strain parameters. The model parameters were based on high quality laboratory testing of the fill and Bay Mud. The tests included isotropically and $K_c$-consolidated triaxial and direct simple shear tests (Dames & Moore 1986). The analyses showed that the stresses within the liner would remain within allowable levels, but that BART tunnels would "oval" vertically due to the stress relief induced by MUNI tunnel excavations. Vertical deformations were conservatively estimated to be in the range of 17 mm to 21 mm, which was considered acceptable. These estimates were predicated on controlled excavation of the MUNI tunnels and the installation of an extensive instrumentation system. An observational approach was adopted whereby excavation techniques were adjusted if measured tunnel deformations exceeded pre-determined levels.

4 MUNI TUNNEL CONSTRUCTION

The MUNI tunnels were excavated under compressed air using an open face shield. The system provided easy access to the tunnel face and permitted orderly removal of piles and other obstructions. The face was supported by wooden breasting boards at all times to prevent sudden face collapse. One or two breast boards were removed at a time to excavate the material and then secured back in place. This elaborate procedure limited the advance rate of the tunnel shield from about 0.9 to 4.5 m per day.

The maximum air pressure used in the tunnels was 83 kPa. The compressed air helped reduce water inflow into the tunnel excavation and also reduced the overload factor to minimize yielding of the clay. The compressed air was effective when the tunnel face was in clayey soils, and became less effective as the cohesion in the soil decreased.

The support for the MUNI tunnels consisted of a steel segmental lining similar to that used in the BART tunnels. The steel segments were erected inside the tunnel shield and grout was pumped to fill the annular space between the steel segments and the shield. After the shield cleared the segments a second grouting operation was conducted to fill voids remaining behind the shield. Hydrophilic gaskets were installed between liner segments to prevent water leakage into the tunnel after the compressed air was turned off at the end of tunneling. A gold rush era ship was encountered during the MUNI north tunnel excavation. The ship was encountered before reaching the zone above BART tunnels.

The area near the Spear street shaft was chemically grouted to reduce the potential for air leakage through the sands in the area. Grouting also reduced the risk of blowout during pile removal. Grouting was extended down to the Bay Mud interface. Grouting covered the footprint of the two tunnels along a length of 66 m from the Spear street shaft.

5 BART TUNNEL INSTRUMENTATION

As part of the "observational approach" to the project a monitoring program was implemented to assess BART tunnel performance during construction and to provide timely data to make changes in the MUNI tunneling procedures if necessary.

The monitoring program included the following components:

1. Field Surveys to measure tunnel liner deformations. The field surveys consisted of a) measurement of spring line convergence using a tape extensometer, b) measurement of crown and invert elevations, c) measurement of tunnel coordinates at the springline level and in the crown using reflectorized
markers and optical surveys, d) train track and third rail elevations and lateral offset. These surveys were done at 8 m intervals every night during the excavation of the MUNI North Tunnel and once a week during the excavation of the MUNI South Tunnel. The surveys could only be conducted within a 3-4 hour period after midnight when the train service was normally shut down. Field personnel accompanied the survey crew to visually inspect the tunnel liner condition.

2. Electrolevel settlement monitoring (EL-Beam) System: An EL-Beam system was used to monitor vertical movements in the BART tunnels. Individual EL-Beam sensors consist of a rigid metal beam fitted with an electrolytic tilt sensor. The 1.5 m long beams used on the project were mounted on brackets firmly attached to flanges of the BART steel tunnel liner. A total of 48 beams (72 m) were used in three clusters of 16 beams each connected to multiplexer units for electronic readout of data. The readout units were connected to a data logger, which was read via a laptop computer on site or remotely via a modem. The clusters were leapfrogged one at a time as the MUNI tunnel heading advanced. The logger recorded readings taken, over a period of about a second, at five minute intervals. A PC located in the instrumentation engineer’s office (Bechtel) auto-dialed the data logger at 30 minute intervals and downloaded the data, which were then transferred to a network server for storage. The system was connected to a telephone pager carried by the instrumentation engineer on duty. The pager was automatically activated when the predetermined alert levels, which ranged between 6 mm and 7.5 mm, were exceeded. A single set of EL-Beams was used and placed in the tunnel directly below the MUNI tunnel being excavated (i.e. the EL-Beam system was in the BART north tunnel during MUNI north tunnel excavation and in the BART south tunnel during MUNI south tunnel excavation).

The EL-Beam system was installed about 2 months before the start of tunneling to provide ample time to establish the reliability of the system. Readings from the system showed a drift in the data and measured movements before the tunneling occurred. This movement was small (less than 0.1 inch) and was attributed in part to inherent tunnel movement similar to those measured using field surveys. Signal noise was occasionally detected in the readings especially in the early hours after midnight. This noise was limited and did not significantly impede the reliability of the system. The cause of the noise remained undetermined.

3. Surface settlement points: Lines of settlement points were located perpendicular to the tunnel alignments. Surface settlement measurements were not a direct measure of the impact of tunneling on BART, but gave an indication of the quality of the tunneling operation and the degree of face control.

The complexity of the instrumentation program and involvement of several agencies required considerable coordination to ensure that measurements were transmitted on a timely basis to all concerned parties, and that a quick response action would be implemented if required.

6 BEHAVIOR OF BART TUNNELS

The MUNI north tunnel was driven first followed by the south tunnel. The MUNI north tunnel drive caused deformations mostly in the BART north tunnel and had minimal impact on the BART south tunnel. Similarly, the MUNI south tunnel drive mostly impacted the BART south tunnel with negligible impact on the BART north tunnel. All deformations were less than 12 mm, well within pre-construction predicted deformations, and were very similar for both BART tunnels. Throughout construction, there was no need to adjust the construction procedure in the MUNI tunnels since all indicators of movement in the BART tunnels remained well within the design values.

Figure 2 is a plot of deformations in the BART south tunnel after completion of MUNI north Tunnel Excavation and during MUNI south tunnel excavation. The figure shows the location of the MUNI south tunnel heading corresponding to the dates of the measurements. Figure 2a shows the total vertical movement in the BART south tunnel at the invert, springline and crown. Figure 2b shows the BART south tunnel convergence or extension horizontally at the springline or vertically between the crown and the invert, calculated as the difference between the measured vertical deformations shown in Figure 2a.

At the end of MUNI north tunnel excavation there was some minimal distortion of the BART south tunnel. At a distance of about 150 m from the Spear street shaft, where the MUNI north tunnel crosses over the BART south tunnel, Figure 1, the BART south tunnel crown experienced 5 mm of heave while the invert experienced less than 1 mm of heave. Closer to Spear street shaft, the BART south tunnel experienced downward movement in the crown and invert of about 5 mm. The springline experienced an extension of about 4 mm and the crown-invert converged about 4 mm. This is probably due to the sideways distortion that the BART south tunnel experienced during the MUNI north tunnel drive.

After the completion of the MUNI north tunnel and as the MUNI south tunnel face advanced towards the Spear street shaft, the BART south tunnel experienced heave and ovalling of the lining. Measurements showed that the tunnel crown moved vertically downwards ahead of the tunnel shield. This is possibly due to the squeezing of the soil ahead of the MUNI tunnel due to shield shoving. As the tunnel shield passed by, the tunnel crown moved vertically upwards due to the relief of the overburden pressure induced by material removal in the tunnel above. The heave in the crown, Figure 2a, followed very closely the MUNI tunnel heading advance. Maximum upward vertical movement was about 12 mm in the crown. Maximum invert heave was about 5 mm. Figure 2a also shows the tunnel vertical deformations measured using the EL-Beam system placed at the tunnel springline. The EL-Beam measurements closely matched the movement measured in the crown. The EL-Beams were periodically surveyed and movements of the EL-Beams were within less than 1 mm of the electronic readouts obtained from the beams. The use of EL-Beams was very successful. The EL-Beams provided continuous deformation data.
of the BART tunnels without the need for frequent physical access to these tunnels.

Figure 2b shows that due to the MUNI south tunnel drive, the tunnel converged at the springline. Springline convergence was almost equal to crown-invert extension confirming the ovalling deformation of the tunnel. The convergence/extension of the tunnel did not exceed 8 mm.

Measurements of lateral offset of the train tracks did not show any trends consistent with the progress of the MUNI tunneling. The maximum lateral offset of the BART tunnel tracks was about 2.5 mm. Track offset was corrected as part of routine rail maintenance and calibration operations.

The BART tunnel lining showed no evidence of denting or similar damage. The field surveys showed increased water and compressed air leakage at tunnel segment joints due to flexing of the tunnel. The leaks were within a few rings ahead and behind the MUNI tunnel heading. Most of these leaks subsided at the end of tunneling. Surface settlement along Market street was less than 75 mm. The settlement troughs extended about 6 m on each side of the tunnel centerline. The surface settlements were mostly a function of the type of ground and extent of grouting above the MUNI tunnels and did not correlate with measured movement in the BART tunnels.

7 CONCLUSION

The construction of the MUNI tunnels as close as 1.2 m above the existing operational BART tunnels was successfully completed with no disruption of the BART train service. MUNI tunnel excavations were conducted under controlled conditions to maintain face stability and minimize deformations. The instrumentation program provided reliable and continuous measurement of BART tunnel movement during MUNI tunnel excavation. BART tunnel deformations were less than 12 mm. The measured deformations were well within the pre-construction estimated deformations. This shows that the numerical analyses can provide reliable estimates of ground movements.

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