Tunneling through an operational oilfield and active faults on the ECIS Project, Los Angeles, CA, USA

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ABSTRACT: A 2.5 km (1.8 mile) long tunnel has been driven by a 4.7 m (15.5 ft) diameter EPB-TBM through sands and gravels of the Lakewood formation and very stiff massive clays and silts with minor occurrences of sand of the San Pedro formation. The Unit 1, western section, of the East Central Interceptor Sewer (ECIS) project tunnels beneath major utility lines with shallow cover, crosses the seismically active Newport-Inglewood Fault Zone beneath Baldwin Hills, and navigates through the Inglewood Oil Fields. The paper describes the hazard assessment and construction considerations of tunneling through faults and outlines risk avoidance planning to avoid abandoned oil wells. The paper then describes the performance of the TBM in the different ground conditions encountered, the forward probing method used to monitor for gas and the search for existing oil wells using a magnetometer both in a probe hole from the tunnel and also from the surface. Procedures are included describing the re-abandonment of an existing oil well discovered elsewhere on the project, and how successful implementation enabled the project to proceed safely.

1 INTRODUCTION

1.1 ECIS project

The NOS-ECIS alignment presented in Figure 1 is approximately 18.5 km long (11.5 miles), and extends from the NORS connection located in the Baldwin Hills area of Culver City, westerly along Exposition Boulevard towards downtown Los Angeles. The eastern end of the alignment terminates just east of the Los Angeles River, near the intersection of Mission Road and Jesse Street. The alignment is primarily located within the densely developed urban area of central and south central Los Angeles.

The tunnel is divided into four construction units with start and end points corresponding to locations of working and retrieval shafts used for tunneling. A general presentation of the design is presented elsewhere by Hanks et al. (1999). Aspects of construction for portions of the project are presented by Crow et al. (2003), and Budd & Goubanov (2003). This paper addresses aspects of tunnel construction on Unit 1.

1.2 Unit 1

The tunnel was driven 2.5 km (8200-ft) from the Siphon Structure near the intersection of Jefferson Boulevard and LaCienega Boulevard to the North Outfall Replacement Sewer (NORS) connection structure (Figure 2).

The tunnel drive was downhill at a constant gradient of 0.12% from east to west over this reach. The EPB-TBM used for mining the tunnel was manufactured in Toronto, Canada by Lovat Inc. and commissioned as “Angie”. The TBM was 4.72 m (15.5-ft) in diameter and weighed approximately 283 tonnes (624,000 lbs).
Along the alignment, one maintenance hole was constructed 1680 m (5512 ft) from the NORS connection shaft, which served as a ventilation shaft. Cal-OSHA required the installation of an emergency rescue chamber after a maximum distance of 1524 m (5000 ft) without a ventilation shaft. All excavated soil was removed from the Siphon Outlet Shaft (Figure 4) at the intersection of LaCienega and Jefferson Boulevards.

2 UNDERGROUND CONDITIONS

2.1 Topography

The longitudinal section of the tunnel alignment is presented on Figure 5. The tunnel alignment on Unit 1 is beneath the steep hilly terrain of the Baldwin Hills from the intersection of La Cienega Boulevard and Rodeo Road to the NORS connection over a distance of about 1.8 km (5905 ft). The alignment of the eastern section of Unit 1 is beneath ground of low relief. The tunnel invert is approximately 16 m (52.5 ft) below ground at the eastern end (siphon outlet) and approximately 23 m (75.5 ft) below ground at the NORS connection. At the deepest location beneath Baldwin Hills, the tunnel invert is 112 m (367.5 ft) below ground surface.

2.2 Geological setting

The project is located in the northern margin of the L.A. basin (Yerkes et al., 1965), described as a 75 by 20 km lowland coastal plain that slopes south and...
Mining across the area identified as the Baldwin Hills Fault (Station 18+10), there did not appear to be any significant change in material. Methane gas registered at 15% and 18% LEL roughly 30-50 m past the proposed fault location. The gas occurrences were read by the handheld instrument at the discharge point of the TBM screw conveyor, typically only associated with the first TBM advance of the day, and quickly dissipated. The identified fault near Station 16+90 manifested with an increase of groundwater, causing the annular grout to become excessively wet and blow through the tail seal brushes.

Excavated soil between Stations 16+18 to 14+10 was described primarily as soft clay with fine sands. Near Station 15+70, a pocket of methane gas registered a 55% LEL and quickly dissipated, accompanied by an increase in volume of cleaner groundwater. After mining through the Inglewood Fault (Station 15+10), material did change to a sandy, silt clay within the zone of Stations 14+70 to 14+95. The increase in groundwater was enough to require pumping. The TBM was out of the groundwater condition by Station 14+60.

Near the Station 11+60 fault, material was still described primarily as a clay with fine sand, with pieces of sea shells were noted as present in the excavated soil until Station 11+15. The soil between Stations 9+44 through 8+31 was described as especially hard clay by the Inspector.

From Stations 6+30 through 4+73, in some of the deepest sections from the surface topography, the very hard clay was described as “squeezing ground”. During probe hole drilling, the steel augers became almost impossible to remove requiring probe holes to again be drilled the following day.

After the Station 00+95 fault, the excavated soil became soft, silty clay with an increase in sand and later also gravel.

One unique feature was the discovery of a pre-existing void at Station 12+90 during the normal probe hole drilling ahead for gas testing. The void encountered extended approximately 6 m (20-ft) horizontally from the TBM face. The probe hole was advancing through the same tight dry clay that had been the case for a number of previous probes. No water or gas was encountered when the void was found. PVC pipe casing was inserted into the probe hole and used for pumping approximately 4.6 m³ (6 cu yd) of grout to fill the void. The same grout normally used for the segment annulus was used to fill this void.

### 2.5 Contaminated soil

A 150 m reach of the Unit 1 alignment (Station 19+00 to 20+50) was beneath soil containing weathered gasoline and sewage. The contamination area was at the intersection of LaCienega Boulevard and Rodeo...
Road where the tunnel passes beneath the existing North Outfall Sewer (NOS) and both existing and former gasoline service stations. The contract provided a unit price bid item for the excavation, handling and disposal of this material if necessary, including specific requirements for safe handling of the material.

The tunnel horizon did not encounter any contaminated soil within the possible identified zone of 150 m. However, the unit bid item was utilized for the excavation, handling, and removal of oil contaminated soils within the ECIS-NORS connection shaft worksite area.

3 OIL WELLS

3.1 Determination of position of oil wells

The alignment passes through the Inglewood oilfield. This oil field produces from sandy reservoirs hundreds of meters deep, but oil and gas commonly seep towards the surface. Not only was there a possibility of intercepting these deposits, but there was also the possibility of encountering old wells. Prior to the award of the contract, the City produced a plan that identified the boundaries of the oil field, based upon the economic limits of ongoing oil production leases. Numerous oil and gas seeps were also reported to the City (Geotechnical Services and Street Services) over the years, manifesting the migration of oil and gas outside of the oil field along faults, fractures, bedding planes and within permeable sediments. The contract plans incorporated the location of both existing and abandoned oil wells on record with the State Department of Oil & Gas and Geothermal Services (DOGGR). An extract from the plans included as Figure 6 shows the tunnel alignment passing through the operational Inglewood oilfield; the black circles indicating oil wells.

Facilities associated with past and present oil production, including sumps, drilling ponds, areas of past spills, storage tanks, exploratory and production wells may also be responsible for release of hydrocarbons into the subsurface soils. Moreover the presence of crude oil in the subsurface due to past leakage or spillage is a potential source of contamination with potential to produce methane gas as a by-product. From previous studies, it was known that prior to 1942 wells were abandoned with drilling mud rather than a deep 150 m cement plug, possibly allowing gas to migrate to the sewer invert and be encountered during construction of the tunnel.

The alignment was set to avoid these wells, however it was expected that unrecorded or “wildcat” oil wells might lie on the tunnel alignment. Precautions were therefore taken to investigate for their presence. These unknown wells were not likely to have been abandoned to modern standards, so significant risk to tunneling, but also the risk of cost being incurred in treating the wells to current standards should that be required.

3.2 Risk management

As the possibility of encountering an unrecorded oil well during tunneling had been identified as a significant project risk by the City and the Contractor, a joint task force worked with the State Department of Gas and Geothermal Reserves (DOGGR). Based upon a review of the DOGGR maps, it was anticipated that tunnel mining would be no closer than 6 m to any mapped oil well, and that there were likely to be some 18 oil wells within 45 m of the tunneling activities. However, to reduce risk of unmarked oil wells, historical documents were also researched and magnetometer studies were performed to search for possible oil wells, observed as magnetic anomalies from both the alignment surface and from within the TBM.

3.2.1 Historical research

A combined effort by the City Geotechnical Engineering and Construction Management Staff, the contractor, and a specialist oil field consultant was made to research information from the following sources:

- Survey and Operational records of all past and present wells on the oil field lease of Plains Exploration & Production, (PXP).
- Historic aerial photographs from University of Southern California archives.
- Los Angeles County area maps.
- Historic and current oil field maps (DOGGR)
- Topographic maps for features of possible past oil well working sites.
- ECIS alignment was surveyed, marked along the ground surface, and walked for visual surface indicators including graded areas and foundations.

3.2.2 Surface magnetometer survey

The City commissioned MACTEC Engineering & Consulting, Inc. to perform a geophysical investigation to search for oil wells within a 12 m by 760 m corridor corresponding to the ECIS alignment through the

Figure 6. Tunnel alignment passing through the operational Inglewood Oilfield.
subject oil field in Culver City. Specifically, the magnetometer would search for undocumented steel well casings. The magnetometer measures the magnetic field intensity using the hand held equipment as shown in Figure 7.

This equipment consisted of a Geometrics Model G-858 magnetometer and GPS system (Trimble ProXRS) for horizontal positioning. A second base station magnetometer was installed at a fixed location to monitor the natural time-varying magnetic drift cycle and record any bursts of magnetic noise that might affect the survey data. Prior to the survey a test survey was performed at a known abandoned well location (TVIC-15) in order to establish a characteristic magnetic signature for abandoned wells within the survey area. Total magnetic field of the test magnetic anomaly was approximately 53,000 nanoTeslas (nT).

In addition, a utility locating survey was performed to identify potential sources of magnetic interference (i.e. buried metallic utilities) so the associated responses would not be mistaken for indications of abandoned wells. The utility locating survey used a Radiodetection Corp. RD-400 radio-magnetic utility locating system and a Fisher Model TW-6M-Scope.

3.2.3 Results of surface magnetometer
This information was processed and presented graphically in relation to the tunnel alignment as shown by the example in Figure 8. Fortunately, the survey indicated no wells in the tunnel alignment. The most significant magnetic anomalies appeared over a surface pad with some abandoned structures, which was considered as a possible previous oil well site.

However, the signature of the anomaly was only indicative only of relatively small, shallowly buried metal objects (Figure 8) dispersed over an 8 m area, and did not match the signature of the known oil well test survey.

3.3 Forward probing for gas, and tunnel magnetometer survey
Contract Specifications required the contractor to probe ahead of the TBM once gas might be encountered beginning at the Baldwin Hills Fault (Station 18+10). The Unit 1 tunnel was classified as “Gassy” by the Cal-OSHA Mining & Tunneling Unit. Probing to perform gas testing was performed in accordance with the Cal-OSHA Tunnel Safety Orders, requiring a minimum of at least 6.1 m (20-ft) of tested ground to remain beyond the face of the TBM.

Upon reaching Station 7+50, specifications required magnetometer surveys for the remainder of the drive to Station 0+00 in order to locate any possible abandoned oil well casings. After probe drilling roughly 58 m (190-ft) with 19 sections of 100 mm (4-in) drilling auger, the drill sections were removed and replaced with a 46 m (150-ft), 75 mm (3-in) PVC casing. The magnetometer instrument, a FVM-400 Vector Fluxgate Magnetometer by MEDA, was inserted in the casing and forwarded to the end of the casing with a fiberglass rod. The instrument was then backed out of the PVC casing at 0.3 m intervals and a data reading taken. Following data collection with the magnetometer, the same basic procedure was repeated but with the insertion of an inclinometer, specifically a Little Dipper by Applied Geomechanics. Data was stored in a Handspring Visor PDA and utilizing Palm OS-compatible software. The inclinometer provided information to determine deviation of the probe hole from the TBM to the end of the casing.

Data collection from the magnetometer was downloaded to produce a graph of the magnetic field against the Station, for the x, y, and z components. A near constant slope of the graph downward after leaving the TBM influence area represented a “normal” condition. Actual plots depicting a spike in the slope on any
of the three components indicated a magnetic anomaly in a particular Station range.

The left side of Figure 9 for the magnetometer probe readings forward of Station 0+532.5 indicate apparent x & z anomalies, whereas the probe readings forward of Station 0+696 depicted on the right indicate “normal” xyz.

The total magnetic field at the station of an anomaly was determined separately by the contractor’s geophysicist, Spectrum Geophysics, after removing the Earth’s magnetic field and the field from the TBM from the data. The largest Total Resultant Magnetic Field was 27,646.0 nT. When anomalies were significantly present, the speed of the TBM was reduced and the mining operation proceeded ahead carefully.

In some instances, an actual surface exploration was made along with review of DOGGR records to again check if there was any overlooked possibility of an oil well. Communication with the on-site oil-production company, PXP, was also very helpful in the process of reviewing records. Mining of the Unit 1 tunnel was successfully completed on August 8, 2003. Due to site access problems, there was a significant delay in mobilization for NORS shaft excavation. To enable completion of the tunnel drive, the TBM was not driven into the shaft, rather the shaft was later constructed around the TBM. The completed shaft is shown in Figure 10.

3.4 Treatment of existing abandoned oil well

Although no oil wells were encountered during Unit 1 tunneling, an abandoned well was discovered at the other end of the project alignment as excavation began for slurry trench guide-walls at the Mission & Jesse work site (Figure 11). The abandoned oil well had been cut-off below the surface and as luck would have it, was located within the rectangular shaft site perimeter.

Fortunately the oil well was not located in conflict with the actual slurry wall footprint. A more thorough review of DOGGR records was performed for oil fields along the western portion of the project alignment, but the single isolated well on the easternmost portion of the alignment went undetected.

Removal of the oil well was critical as shaft design required excavation to 26 m (85-ft) below the ground surface. The shaft location could not be moved due to the confined nature of the site. Staff worked quickly with a DOGGR field engineer to identify the well, which was recorded abandoned in the 1940’s.

However, to modify the well casing in any way would require the well to be treated according to present day standards for abandonment. By way of a change order, the contractor provided an oil field welder to remove the well cap and allow DOGGR to determine
whether the previous plug was secure and that there was no gas leakage. The City enlisted a DOGGR approved consultant, Sampson Oil, to perform the oil well research, coordinate the permit application with DOGGR, and oversee the oil well abandonment process. The contractor hired subcontractor Oil Field Services, Long Beach, a capable contractor who was able to mobilize, drill out the existing well 215 m (700-ft), install a new cement plug, and demobilize within five days. The equipment used is shown on Figure 12.

The cement plug of a mix proportion of 100 kg of cement to 45 liters of water was poured in two stages of total volume 20 m$^3$ (725-ft$^3$). Considerable uncertainty surrounded the treatment of this old well, as it might have been filled with discarded oil pipe, pipe retrieving tools, wood, or any other kind of debris available at the time to fill the hole in. Fortunately, the hole was fairly clean except for a difficult wooden plug, and drilling took fewer than three days as opposed to potentially 2–3 weeks. After the slurry trench reinforced concrete guide walls were completed followed by shaft excavation, the existing well casing was cut off in segments as the excavation progressed. In this situation, the well was finally cut-off roughly 1.5 m (5-ft) below the working level of the shaft and sealed with a welded steel plate cap. DOGGR and a representative from LAFD inspected the plugged well casing prior to welding of the final steel plate cover.

The effort required to abandon this unmarked oil well properly provided the necessary motivation early in the project to further research the alignment of the Unit 1 tunnel for any other unmarked oil wells which might exist. Potential impact both to project schedule and budget was a real concern. If encountered, the process for abandonment of oil wells along Unit 1 would have required further efforts to obtain surface rights, locate and excavate for the well head, and provide access for the necessary equipment. Fortunately, the oil well at the east-end of the project was the only one encountered.

4 TBM PERFORMANCE

4.1 EPB TBM

The contractor, a joint venture of Kenny Construction Co./J.F. Shea Co. Inc./Traylor Brothers, Inc./Frontier-Kemper Constructors Inc. (KSTF-K) chose to use a TBM machine manufactured by Lovat. A cross section of the EPB machine is presented in Figure 13; however a comprehensive description of the machine is contained in Crow & Holzhauser (2003) and Budd & Goubanov (2003).

4.2 TBM production

Although the TBM performance for the remainder of the ECIS project was presented in Crow and Holzhauser 2003, a brief summary is provided herein.

Tunneling of the 2.5 km long tunnel on this Unit started on October 13, 2002 from the Siphon Outlet Shaft to the East and was completed on August 8, 2003. An overall average progress rate of 247 m/month has been achieved.
4.3 Settlement

The surface settlement measured along Unit 1 in both granular and cohesive materials was less than 10 mm. Subsurface measurements using multi-point borehole extensometers were undertaken. In general, the lower anchor located at 1.5 m above the crown of the tunnel measured less than 32 mm settlement.

5 CONCLUSIONS

- Tunnels can be successfully driven through active oilfields, but the importance of adequate site investigation, risk assessment, good planning and implementation of these plans undertaken should not be overlooked.
- Tunneling through faults in soft ground with a closed face TBM can be achieved with good site investigation, planning and co-ordination on the part of the owner, designer and contractor.
- Surface and forward probe magnetometers are useful tools in reducing the risks of tunneling through active oilfields, but they must be used with care and their records interpreted by experienced geophysicists.
- The removal of the environmental nuisance of inadequately abandoned oil wells can be safely and readily achieved with the assistance of experienced oilfield engineers and contractors.

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REFERENCES