Microtunneling through Abrasive Soil with Cobbles and Boulders: Construction of the Santa Ana River Interceptor (SARI) Relocation

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ABSTRACT: The Santa Ana River Interceptor (SARI) Relocation Project in Yorba Linda, CA will relocate four miles of existing interceptor sewer pipeline out of the Santa Ana River scour zone. Approximately 4,700 feet of the product pipe will be installed by 77 to 101.5-inch diameter microtunneling in 5 segments, including 2 siphon crossings and 2 curved tunnels, one of which is a 1,567-foot S-shaped alignment. Tunneling was chosen to avoid construction impacts to the community and environmental impacts along the river. One of the tunnels may cross the Whittier-Elsinore Fault Zone.

Soil conditions on the project include a complex mix of alluvium with abundant cobbles and boulders in a weak sandy matrix. During design, subsurface investigation reports indicated abrasive soils based on Miller testing. Groundwater levels are well above the pipeline elevation during flood season along several of the tunnels. Temporary shaft structures are excavated up to 70 feet deep and include the use of cement deep-soil mixing, secant piles, and soldier pile and lagging walls with permeation grouting designed to limit groundwater inflow.

This paper describes how the microtunnel machine was selected based on the anticipated geotechnical conditions and how it performed in this environment. The machine design included the capability of compressed air face access. The relation between soil abrasivity laboratory testing and equipment wear and tool life is presented. Information related to planning and constructing curved drives is offered.

1. INTRODUCTION

Construction of the Santa Ana River Interceptor (SARI) Relocation Project began in mid 2011 with the start of the Yorba Linda Spur (YLS) contract and is expected to be complete by 2014. The project consists of the following two contract packages:

(1) SARI YLS Contract – Picks up domestic wastewater from the City of Yorba Linda that currently flows into the existing SARI, but will be unable to once the new SARI is relocated to its new alignment on the other side of the river. It consists of 4,685 feet of 15-inch gravity sewer, including 794 feet of siphon pipes inside a 77-inch outside diameter (OD) casing pipe installed via microtunneling under the Santa Ana River for the construction of a twin barrel 12-inch siphon with a 16-inch overflow, and odor control facilities. The project was awarded to LA Engineering for $7.2M.

(2) SARI Mainline and Metering Station (Mainline) Contract – Consists of approximately 20,700 feet of 54-inch diameter gravity sewer, with several reaches of 101.5-inch OD casing installed via microtunneling. Work includes installation of gravity sewer and casing behind an existing tie-back wall; open trench construction within Canyon RV Park; crossing a documented wildlife corridor adjacent to the Santa Ana River and State Route 91 Freeway; open trench construction within the Green River Golf Club; and several tunneling segments including two planned curved microtunnels, one that will be the longest multiple curved microtunnel in the United States. The design also includes a new metering station to be located within Canyon RV Park requiring construction of a 30-foot
deep by 25 feet wide and 45 feet long below grade cast-in-place concrete vault. The vault will house parallel 30-inch pipes with magnetic flow meters, isolation valves and water quality testing equipment. An above ground building houses the electrical equipment, restroom and storage. Upon completion of the new facilities, the contractor will complete the demolition/abandonment of the existing SARI pipeline and metering station. The project was awarded to W.A. Rasic Construction for $41.85M. (Agor, 2012)

This paper provides details of the design and construction of the microtunneling drives which involved the use of both steel and concrete casing in difficult ground conditions. At the time of publishing, two of the five following microtunneling drives have been completed:

1. YLS Siphon Crossing Drive *(completed)*
   a. 794’ long; 77” OD; 75.5” ID; welded steel casing
   b. Launch & receiving shafts: unreinforced secant piles

2. Mainline Gypsum Canyon Drive *(completed)*
   a. 622’ long; 101.5” OD; 84” ID; RCP casing
   b. Launch & receiving shafts: soldier piles and lagging with permeation grouting

3. Mainline Siphon Crossing Drive *(planned)*
   a. 1,092’ long; 101.5” OD; 99.5” ID; Permalok casing
   b. Launch shaft: overlapping cutter-soil mix panels and reinforced shotcrete
   c. Receiving shaft: unreinforced secant piles

4. Mainline Coal Canyon 2-Curve Drive *(planned)*
   a. 1,567’ long; 101.5” OD; 84” ID; RCP casing
   b. S-Curved (15,873’ radius curve first, then a 15,518’ radius curve)
   c. Launch shaft: soldier piles and lagging
   d. Intermediate shaft (cutterhead inspection): lattice girder reinforced shotcrete
   e. Receiving shaft (same receiving shaft will be used in other Coal Canyon Drive): lattice girder reinforced shotcrete

5. Mainline Coal Canyon 1-Curve Drive *(planned)*
   a. 622’ long; 101.5” OD; 84” ID; RCP casing
   b. Curved (5,500’ radius)
   c. Launch shaft: soldier piles and lagging
   d. Receiving shaft (same receiving shaft will be used in other Coal Canyon Drive): lattice girder reinforced shotcrete

2. PROJECT BACKGROUND

Constructed in the mid-1970’s, the Santa Ana Regional Interceptor (SARI) Line was originally constructed with approximately 20 feet of cover within the floodway of the Santa Ana River between Weir Canyon Road and the Orange/Riverside County boundary. In some locations, the low-flow of the Santa Ana River has meandered toward the existing SARI Line and the bed of the Santa Ana River has degraded leaving the SARI Line virtually exposed to the river at several locations requiring the placement of temporary rock riprap revetment and grade stabilizers to protect the SARI Line nearly every year.

The U.S. Army Corps of Engineers (Corps) is working with the flood control districts of San Bernardino, Riverside and Orange Counties to complete the $2.1 billion Santa Ana River Mainstem Project (SARMP). As part of the SARMP, the Corps reconstructed the outlet works for Prado increasing its capacity for making controlled releases from 10,000 cubic feet per second to 30,000 cubic feet per second. Additionally, the Corps widened and strengthened the banks of the Santa Ana River downstream of Prado Dam to accept the planned higher releases. Scour studies completed by Tetra Tech as part of this project indicate that a single 30,000 cubic feet per second (cfs) release may cause significant damage to the existing SARI, and that the anticipated releases over the life of the SARMP (one hundred years) could result in additional riverbed degradation and scour nearing 20 feet imperiling the stability of the existing SARI. As a local sponsor for the SARMP, it is the Orange County Flood Control District’s (OCFCD) responsibility to relocate or protect utilities like the SARI Line within Orange County that are impacted by the SARMP. The project alignment is illustrated in Figure 1.

The design team led by Tetra Tech, with tunnel and shaft design by Hatch Mott MacDonald, was retained by the Orange County Flood Control District (OCFCD) to complete the preliminary and final design to relocate the existing SARI, as part of the U.S. Army Corps of Engineers Santa Ana River Mainstem project. Within Orange County, the SARI line is owned and operated by Orange County Sanitation District (OCSD) and maintenance costs are shared with a third agency, Santa Ana Watershed Protection Agency (SAWPA) based upon the capacity used by
SAWPA within this reach of the SARI. This project replaces 3.7 miles of 39- to 45-inch VCP and 42- to 45-inch RCP with 3.85 miles of 54-inch gravity sewer, roughly from Green River Golf Club to the SAVI Ranch control gate structure. (Agor, 2012)

3. **ANTICIPATED GROUND CONDITIONS**

The SARI Mainline and YLS alignments are located in the lower Santa Ana River Valley, below Prado Dam, which lies within a deeply incised gorge. This area is divided between Riverside County to the northeast and Orange County to the southwest between the northern Santa Ana Mountains and southern margin of the Puente Hills, part of the Peninsular Ranges geomorphic province of Southern California.

![Figure 1. Existing SARI line and SARI Relocation line alignments (not to scale).](image)

Both the Santa Ana Mountains and Puente Hills consist generally of sandstones and shale bedrock of Cretaceous to Tertiary age (65 million to 1.8 million years old). The Puente Hills represent a complexly folded and faulted block of Tertiary age marine sediments uplifted between the Whittier fault on the southwest and the Whittier-Elsinore fault to the northeast (Leighton, 2010a).

3.1 **BASELINE SUBSURFACE CONDITIONS**

Based upon the subsurface conditions encountered during the field exploration, their depositional origin and engineering characteristics, the materials that are expected to be encountered during construction are grouped into five units in the Geotechnical Baseline Report (GBR): Sand Mix, Gravel Mix, Silt Mix, Clay Mix, and Bedrock consisting of thinly-bedded Puente Formation and massive sandstone of the Topanga Formation (Leighton, 2010b). The units are summarized in Figure 2.

The microtunnel boring machines (MTBMs) are expected to encounter cobbles and boulders up to 36 inches in size primarily within the Gravel Mix unit and to a lesser degree within the Sand Mix unit. The cobbles and boulders present in the Sand Mix and Gravel Mix are composed of sedimentary, igneous and volcanic rock and could have an unconfined compressive strength up to 30,000 psi.

Representative samples of the Sand Mix and Gravel Mix were tested for slurry abrasivity by ASTM G75 Miller Number Test Procedure. The Sand Mix and Gravel Mix fall into the “Very High” slurry abrasivity category with Miller Numbers of 356 and 377, respectively.
Groundwater was encountered along the entire SARI alignment ranging from the river surface to depths 30 feet below ground surface. The groundwater fluctuates seasonally, during heavy rainfall and increased releases from Prado Dam. The maximum measured increase in groundwater elevations within the alluvial deposits was over five feet and this occurred between the time period of January 15 and January 28 of 2010 during which time seven inches of rainfall was recorded nearby. Various elements of the SARI Relocation Project will be constructed below groundwater, depending on location.

Figure 2. Soil and Bedrock Stratigraphy and Exposed Cut (Leighton, 2010b)

4. **MTBM DESIGN AND CAPABILITIES**

The minimum specified microtunneling requirements were based on the Engineer’s interpretation of the expected ground conditions. The potential exists for groundwater, flowing soil behavior and boulders along the microtunneling alignment that is required to be taken into account when considering the equipment requirement. The specified minimum microtunneling equipment requirements such as face access and compressed air lock is, in part, due to the anticipated abrasiveness of the ground and the possibility of encountering large boulders. All ancillary equipment required to safely operate the airlock and gain access to the face of the MTBM is required to be on site and ready for use prior to the commencement of microtunneling work. Vadnais (YLS subcontractor) and Fowler (Mainline subcontractor) each selected Herrenknecht slurry microtunneling machines with these capabilities.

Compressed air tunnel work has been permitted by CalOSHA in Southern California before. CalOSHA has a process for granting variances away from their decompression tables, if necessary, but this process takes time and needs to be started early. Bidders were encouraged to contact CalOSHA to gain an understanding of what is required to obtain the necessary permits to perform compressed air interventions. Additionally, the contractors each benefited from hiring a specialty dive company as a sub for the compressed air work, if needed, to lean on their expertise. This approach helped clarify what equipment is necessary to perform the work once the variance is obtained.

5. **SHAFT EXCAVATION AND SUPPORT**

The allowed shaft support systems for the different locations were based on constructability, as well as geotechnical and hydrostatic conditions. Options vary for each location and consisted of:

1. Cut-off wall shaft with drained invert
2. Sealed shaft
3. Ring beam and liner plate shaft (low groundwater areas only)
4. Soldier pile and lagging shaft (low groundwater areas only)
The YLS Contractor constructed both the launching and receiving shafts utilizing circular, unreinforced 36” diameter secant piles as seen in Figure 3. The 36-inch size is a minimum required pile diameter intended to ensure sufficient overlap while encountering cobbles and boulders during construction.

The Mainline Contractor is in the process of constructing eight shafts using a variety of techniques including: cutter soil mix (CSM) panels, secant piles, shotcrete and lattice girders, and solid pile and lagging. The Gypsum Canyon Drive included solid pile and lagging shafts (Figure 3) with permeation grouting around the perimeters and at the entry and exit locations.

![Figure 3. Views of the YLS Siphon Crossing launch shaft (left) and the Mainline Gypsum Canyon launch shaft (right).](image)

### 6. ABRASIVITY AND WEAR

Several test methods exist for testing abrasivity of hard rocks that are used to predict cutter wear on hard rock TBMs. These tests cannot be directly applied to soil. The development of standardized tests for measuring the abrasivity of soils is still in a formative stage and testing to characterize soil abrasivity have been applied inconsistently on soft ground tunnel projects. No standard exists to predict wear rates of cutterhead wearing surfaces and cutting tools based on soil abrasivity, and yet soil abrasivity affects the wear rate of tools on the cutterhead and on secondary wearing surfaces that come in contact with the spoil. Excessive wear can lead to unplanned delays and downtime while tunneling and between drives so it is important to characterize soil abrasivity. Slurry TBMs may experience adverse impacts on the slurry components including piping, pumps, hydrocyclones and more. The longer the tunnel drive, the more severe the abrasion due to the longer exposure of the slurry system to the spoil mixed within the flowing fluid. Contractors benefit when they can understand the level of expected abrasion when bidding projects. Unfortunately, few tests prior to tunneling conclusively determine the soil-induced abrasion of the steel during TBM tunneling.

The standardized test selected for the SARI project was the Miller Number Test. Testing results were incorporated into the GBR that was provided to bidders for use in preparing bids and will be used if necessary during construction if there is a notice of a differing site condition related to soil abrasivity to assess a claim.

The Miller test (ASTM G75-01) was originally developed for slurry-pumping systems in the mining industry for deep vertical borings in 1967. Its purpose is to rank the relative abrasiveness of soil-slurries to a reference material. For this test, a standardized steel block is dipped into the test slurry contained in a neoprene-covered tray, and is loaded with a fixed weight. Slurry is prepared by first running the soil sample through a sieve to remove the fraction larger than 1-mm before it is mixed (50% by mass) with de-ionized water. The steel block is driven in a reciprocating motion through the test slurry for 6 hours. The loss in mass of the steel block gives the Miller Number which is an index of the relative abrasivity of slurries.

At the time of publication, two of the five SARI tunnels have been completed: the YLS Siphon Crossing Drive and the Mainline Gypsum Canyon Drive. For these two tunnels, the on-site inspectors from HMM reviewed wear on the first can of the MTBMs for the purpose of collecting empirical data in regards to abrasivity. The amount of wear was then evaluated against the criteria created in Table 1. These criteria were developed for this paper as a “first...
draft” to set the foundation for collecting information on future projects and provide a relation between Miller tests and actual wear of the MTBMs.

Table 1. MTBM Abrasion Levels.

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<th>Level of Abrasion</th>
<th>Description</th>
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| High              | • Gauge disc cutters significantly worn  
                  | • Missing many picks/drag teeth         
                  | • Loss of most hard facing; especially near perimeter of cutterhead  
                  | • All paint missing                     |
| Moderate          | • Gauge disc cutters moderately worn    
                  | • Missing few picks/drag teeth          
                  | • Hard facing minimally lost; mostly near perimeter of cutterhead  
                  | • >50% exterior paint missing           |
| Low               | • Gauge cutters minimally worn          
                  | • Minor wear on tips of picks/drag teeth  
                  | • Almost no loss of hard facing         
                  | • <50% exterior paint missing           |

7. SUMMARY OF GYPSUM CANYON TUNNEL EXCAVATION

WA Rasic’s tunneling subcontractor, James W. Fowler Co., began the Gypsum Canyon Drive in mid-October and finished contact grouting in mid-November 2012. This tunnel drive is 622-foot long and ranges between 14 to a maximum of 28 feet below ground surface to tunnel centerline. The baseline ground conditions were the following:

• ~480 feet of mixed-face conditions with Gravel Mix over Sand Mix  
• ~120 lineal feet of Sand Mix  
• ~20 lineal feet of Gravel Mix  
• Cobble and boulders will likely be encountered  
• Number of boulders of approximately 36 inches in size measured along the longest dimension: 2  
• Baseline groundwater elevation above invert but below crown of tunnel

It took 17 days (day shift only) to completely launch the 44-foot long Herrenknecht AVND-2000AB MTBM into the ground that bored a path for the 101.5-inch OD RCP casing pipe. Before half of the first MTBM section was excavated, approximately 15 of these days were lost due to a hydraulic pump and also an electrical power plant failure. What remained of the 622-foot tunnel was constructed on a day-shift basis and took 16 days for the MTBM to reach the receiving shaft seal. No interventions were necessary on this drive. Extraction of the MTBM occurred over a two day period. Removal of equipment from the tunnel took place over a 10 day period. Contact grouting of the entire tunnel was performed in just over two days.

The 622-foot long Gypsum Canyon Tunnel experienced a moderate amount of wear based on the description in Table 1 and shown in Figure 4. The rolling distance of the gauge cutters was approximately 125 miles. The Gypsum Canyon MTBM passed through approximately a total of 20 feet of grouted soil; estimated to be less than 200 psi in strength, placed by permeation grouting.
8. SUMMARY OF YLS TUNNEL EXCAVATION

LA Engineering’s tunneling subcontractor, Vadnais Corporation, began the YLS Siphon Crossing Drive in mid-May and finished contact grouting in mid-June 2012. This tunnel drive is 794-foot long and ranges between 16 to a maximum of 28 feet below ground surface to tunnel centerline. The baseline ground conditions were the following:

- ~70 lineal feet of mixed-face conditions with Silt Mix and Clay Mix overlying Puente Formation
- ~730 lineal feet of Sand Mix
- Cobbles and boulders expected to be encountered
- Number of boulders of approximately 36 inches in size measured along the longest dimension: 1
- Tunneling completely below the groundwater table

It took 5 days (12 hour day shift only) to completely launch the 52-foot long Herrenknecht AVND-1600AB MTBM into the ground that bored a path for the 77-inch OD welded steel casing pipe. What remained of the 794-foot tunnel, constructed primarily on a 24/7 basis per contract requirements, took 16 days for the MTBM to reach the receiving shaft seal. No interventions were necessary on this drive. Extraction of the MTBM and removal of equipment from the tunnel occurred over a three day period. Contact grouting of the entire tunnel was performed over six days.

The 794-foot long YLS Siphon Crossing Drive experienced a high amount of wear based on the description in Table 1. The MTBM passed through a total of approximately 8-10 feet of 2,500 psi (design strength) unreinforced concrete secant piles which may have increased the wear rates. The rolling distance of the gauge cutters was approximately 90 miles. As seen in Figure 5, the face of the MTBM used on the YLS Siphon Crossing Drive experienced high wear rates on parts of the cutterhead. Compared with the Gypsum Canyon tunnel, the wear was higher on the YLS gauge cutter discs despite rolling about 30% less distance. The YLS crossing was longer in lineal distance compared to the Gypsum Canyon tunnel, but the operators on the Gypsum Canyon Drive drove the larger diameter machine with a higher average revolution per minute (RPM).
9. PLANNING FOR CURVED MICROTUNNEL DRIVES

The Mainline Contractor, WA Rasic, and their microtunneling subcontractor, Fowler, proposed a value engineering change in the project alignment to add three curves, thus eliminating a tunnel shaft. This revised alignment includes one multiple-curve tunnel (Drive #4) and one single-curve tunnel (Drive #5). The changes yielded a project cost savings over $1M. The curved tunnel alignment is illustrated in Figure 6.

The reason for the curves in the tunnels is due to the narrow right-of-way along the project alignment. To one side of the available right-of-way, is land owned by the State of California, Department of State Parks. The land is dedicated open space, and provides a path used by various animals such as cougars, bears and deer to reach the Santa Ana River from the adjacent hillsides. The other side is owned by the California Department of Transportation (Caltrans) and is dedicated for the 91 Freeway.

The proposed radii are included in Section 1. In reviewing the curved alignments at a scale of 1”=40’, there was very little difference to that of the two straight segments. The large radii resulted in “slight” curves which was a major factor in considering this alternative. Also a major factor was the individuals who will be performing the work have significant international experience, including several curved microtunnel installations.

As stated, the horizontal alignment difference between the bid design and that of the value engineering option is barely visible as shown on the drawings at 1”=40’. As such, all parties agreed that the geology to be encountered in one alignment is the same as the other. It was therefore concluded the owner and contractor maintained the same level of risk as when the project was bid. The next concern is the longer drive length of the curved installation, a natural outcome of removing one of the tunnel shafts which is the vast cost savings with this value engineering submittal. The added risk is the increased potential of having the various components on the tunnel face wear out and either slow or even stop production. If this was to occur, the machine would need to be retrofitted, done via a costly and time consuming compressed air intervention entry to the tunnel face. It was negotiated that should this need occur within the longest tunnel distance of the bid tunnel alignment that the cost would be borne solely by the contractor. Should the need occur at a distance past this length, the cost would be shared by the contractor and owner equally. To limit the owner’s risk exposure, an intermediate shaft was required and included in the final cost savings proposal. (Agor, 2012)

Based on the experience thus far, the following considerations are recommended when designing curved microtunnels:

1. Ensure a qualified surveyor and guidance system manufacturer are engaged
2. Since the pipeline can no longer be located on the surface by the tangent between manholes, the owner may want to consider monuments located on the surface above the tunnel alignment (e.g. Omni Markers)

3. Joint designs that prevent water infiltration while moving through the minimum curve radius plus steering tolerance
   a. On the SARI project, joint deflection is expected to be 0.32 degrees per pipe (assumes a 50% increase due to steering), while the joint capacity is up to 0.99 degrees that still guarantees full circumference contact area with no gaps in the concrete jacking pipe

4. Joint designs accounting for stress distribution of thrust forces through the joints (e.g. Jackcontrol P-type joints with real time monitoring)

5. Additional resources to minimize thrust forces (e.g. additional IJSs)

6. High jacking capacity pipe (e.g. SARI is utilizing ASTM C76 Class V RCP with 877 tons allowable thrust capacity on the curved drives)

At the time this paper is being written, the curved tunnel drives are schedule to be constructed in the first half of 2013.

![Figure 6. View of the Mainline curved tunnel alignments.](image)

**10. CONCLUSIONS**

The project’s geotechnical conditions included challenging ground due to the risk for settlement of roads and the nearby existing SARI line. Also of concern was the fracture of tunnel fluids, abrasive ground affecting the MTBM operation, and encountering ground that may require interventions. Both contractors selected Herrenknecht AVND MTBMs that have successfully excavated the two tunnels completed at the time of publication. The paper presents several recommendations to consider when designing curved microtunnels.

The industry has only a few abrasion test methods available for soils. These tests provide information on the abrasion characteristics of minerals within the soil and of slurry-soil mixtures, but are limited to specific aspects of the abrasion problem. The SARI Project used Miller Tests to baseline the abrasivity of the ground and the wear on the MTBMs was reviewed after completing the tunnel drives. Three categories of MTBM wear are presented within the paper. As more empirical examples are gained from future projects, these categories will be refined.

The microtunneling profession will benefit from more empirical examples being collected in the future to help predict wear rates on soft ground tunnel jobs based on recent experiences on other projects. The authors recommend future projects collect project information that factor in to abrasion of the MTBM and associated costs, such as the following:

- Anticipated ground conditions
- MTBM size
- Cutterhead configuration
- Anticipated shaft wall/grouted zone conditions (length, strength, etc)
- Slurry composition over the length of the drive
- Rolling distance (depends on cutterhead speed, size, and longitudinal distance)
- Classification of visual wear after MTBM extraction
- Amount and cost of repairs/refurbishment after tunneling
To date, several laboratory tests have been used on past soil TBM projects. A few of them include the LA Abrasion test, the Miller test, and the Laboratoire Central des Ponts et Chaussees (LCPC) test. Several limitations in their predictability of TBM tool wear have been identified in each of these tests. Some of them are as follows:

- SAT is not directly applicable to soft ground tunneling as it tests dry soil sample, and only the fraction that is less than 4mm, although larger sizes can be crushed and added upon request. Therefore, it is not representative of in-situ soil conditions.
- Crushing the particles larger than 4mm for inclusion in the SAT test would change the shape of the soil grains, making them more angular and possibly altering the soil abrasivity. This would, however, be conservative since angular grains tend to be more abrasive than non-angular ones.
- The contact stress between the wear pieces and soil samples cannot be tested by standard.
- The Miller Number test was primarily developed to determine the degradation of slurry abrasivity to a slurry pump, and the test currently does not have widespread usage among tunneling practitioners.

A new abrasivity testing device and procedure to simulate in-situ conditions is currently under development by Pennsylvania State University. This testing device will allow testing soils in wet and dry conditions, and is sufficiently big (14-inch diameter and 18-inch long cylinder) to allow testing of bigger size soil particles. It will include variations in ambient pressure as well as rotary speed and torque of a propeller to measure weight loss of test material (propeller blades). This test method could possibly be used to develop a soil abrasion index in the future, but is not currently available for use.

11. REFERENCES


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