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# DEEP FOUNDATIONS

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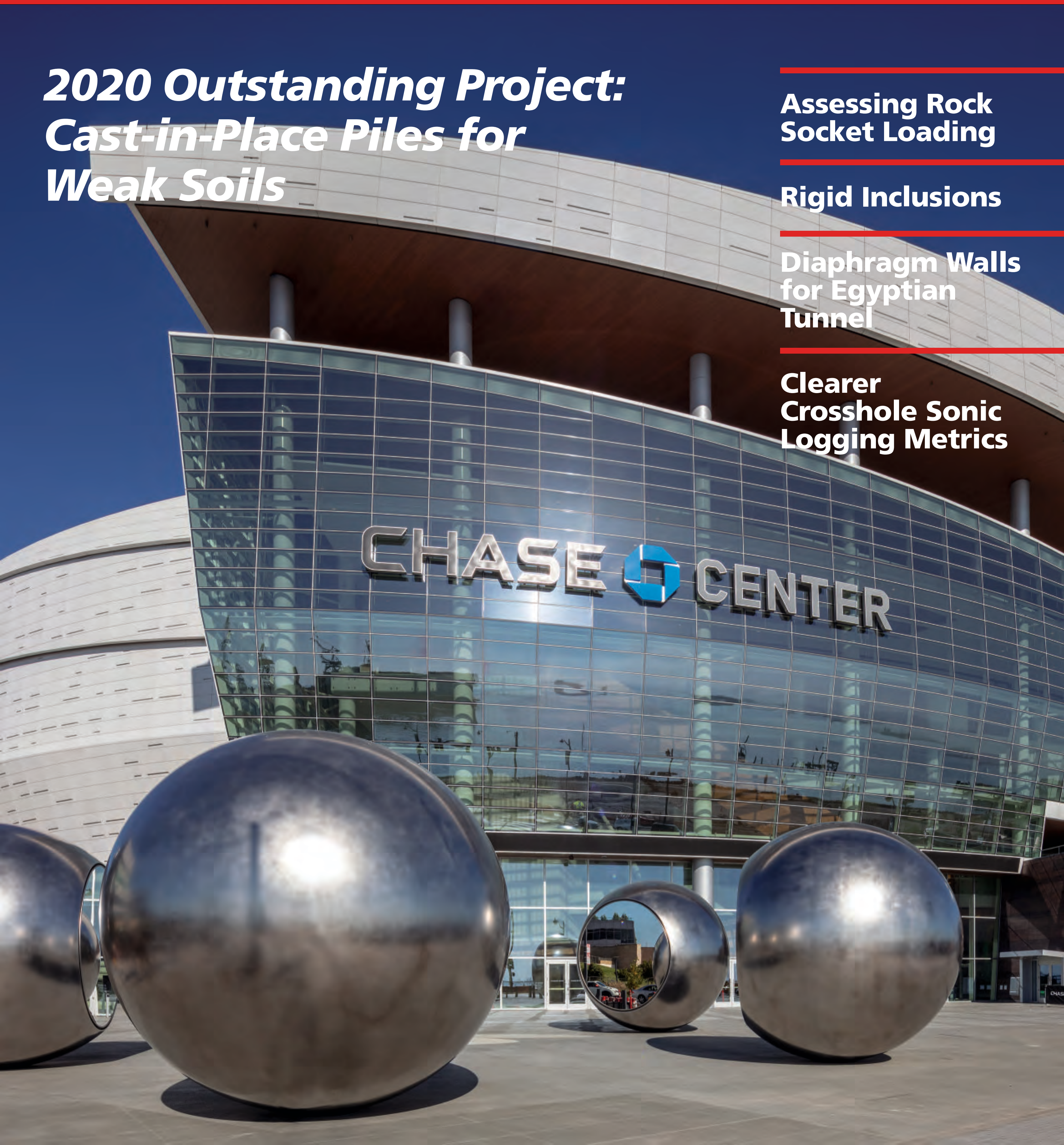

# Diaphragm Walls for Suez Canal Tunnel

Casting operation with 3 mixer

The Suez Canal serves as a major waterway for navigation between Europe and Asia without having to circumnavigate Africa. This artificial canal was built in the mid-1800s in Egypt, west of the Sinai Peninsula, and connects Port Said on the Mediterranean Sea to the Suez on the Red Sea. It consists of two different sections, the northern one of which is the focus of this article, and extends from Port Said to the Great Bitter Lake, south of Ismailia (the southern one connects the lake to Suez).

In 2010, as a result of expansion works, the Suez Canal's length reached 120.1 mi (193.3 km), its width rose to 672.5 to 738.2 ft (205 to 225 m), and the depth was increased to 78.7 ft (24 m), enabling the transit of ships with a draft (draught) of up to 66 ft (20.12 m).

Then in 2014, Egyptian President Abdel Fattah al-Sisi inaugurated the commencement of works to double a part of the canal. Thanks to this expansion, 97 ships, without limits of dimension, are able to transit the waterway on a daily basis.

Moreover, the project included upgrading of road and railway networks and expansion and construction of five trading ports in the Port Said area.

The project, amounting to over $7.2 billion (€ 6.4 billion), was entrusted to the Egyptian Engineering Authority of the Armed Forces (EAAF).

## North Road Tunnel

As a part of the Canal Region Development Plan, the Egyptian government awarded the contract for the construction of twin-tube road tunnels and a railway tunnel under the Suez Canal to two major Egyptian companies: The Arab Contractors (AC) and Orascom Construction Industries (OCI). The railway tunnel aspect was cancelled in 2017.


**Path of road tunnels beneath Suez Canal, south of Port Said**

This article focuses on the construction of one tunnel of the twin-tube road tunnel, which connects Port Fuad Road, on the east side of Suez Canal, to Port Said – Ismailia Highway on the canal's west side. The two road tunnels, located about 12.4 mi (20 km) south of Port Said, allow bypassing the need to use ferries. They will contribute to the expansion of North Sinai, helping enhance the industrial area and the coastal connection between the Sinai Peninsula and the Nile Delta.

The project involved constructing the northernmost of the two parallel underpasses. Each extends about 2.4 mi (3.9 km), at an axis distance ranging from 139.4 ft (42.5 m) at the tunnel entrances, to 98.4 ft (30 m) in the central area, underneath the Suez Canal. These high-traffic density twin tunnels include a two-lane carriageway executed by adopting different foundation techniques.

Cut and cover sections and open U-sections were used for the tunnel ramps, whereas multicellular shafts were used for the tunnel boring machine (TBM) launching and reception zones. Structural diaphragm walls were adopted for the execution of the aforementioned retaining structures.

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Mechanized excavation was adopted for the tunnels, which have inner diameters of 37.4 ft (11.4 m) and lengths of approximately 1.5 mi (2.8 km). A Mixshield TBM was used for each tunnel, which has an excavation diameter of 42.6 ft (13 m). Finally, plastic diaphragm walls were executed for the break-in and break-out blocks.

The project also included six cross passages (CP1 to CP6) connecting the two tunnels that were executed with plastic diaphragm walls. Three of these cross passages functioned during construction as emergency exits and were used to carry out maintenance interventions at the TBM front.

The main contractor (AC-OCI JV) awarded the special foundations works to construct the north-side road tunnel to Trevi, in a joint venture with The Arab Contractors (AC). The work began in September 2015.

Guide wall construction for multicellular launching shaft

## Soil Profile

The site area for the special foundation work is basically flat, with ground level ranging between +4.9 to +6.6 ft (+1.5 to +2.0 m) above mean sea level. The static level of the water table coincides with the sea level.

Soil investigations carried out to define the stratigraphic conditions of the area showed a rather uniform stratigraphy along the entire axis of the road tunnels. In particular, the soil consisted of two geological formations:

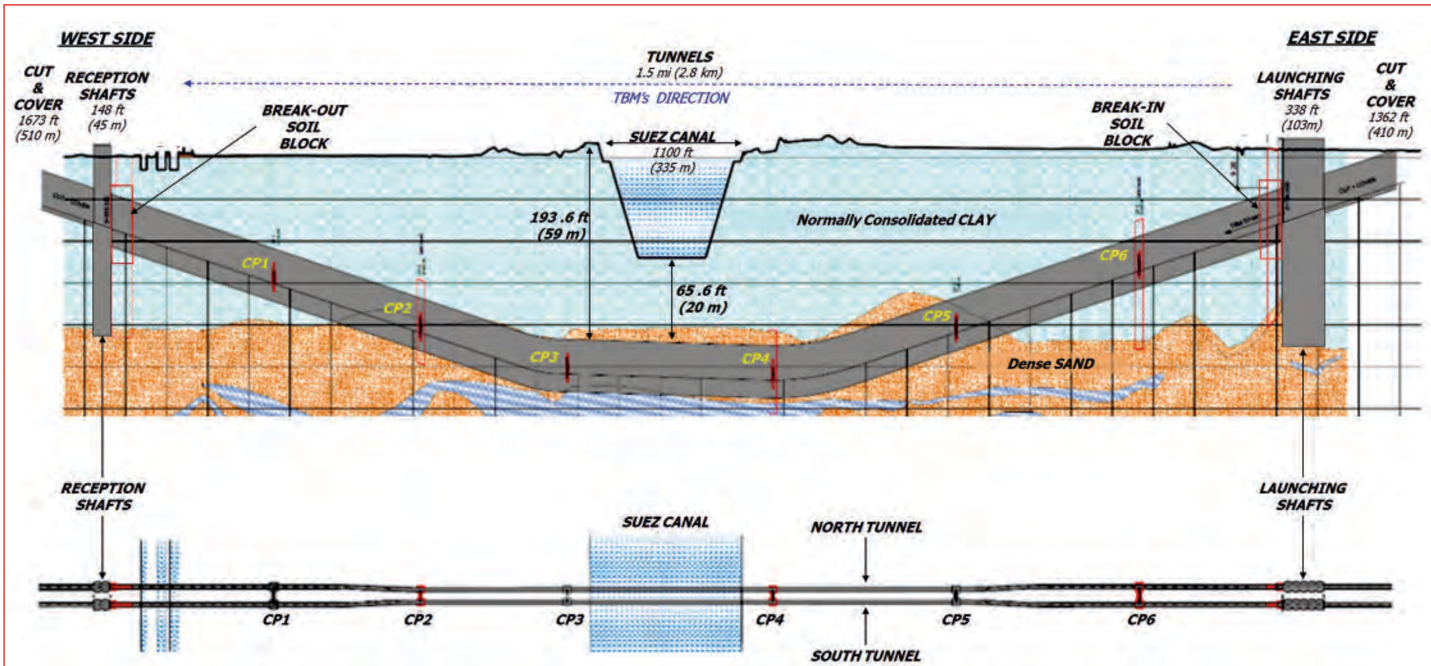
1) Fine materials derived from recent river deposits (Holocene) of the Nile Delta. This normally consolidated, silty clay has a consistency ranging from very soft to firm for the first 131 to 141 ft (40 to 43 m) below ground level.

2) Below that (starting 131 to 141 ft [40 to 43 m] below ground level) lies coarse-grained materials belonging to older Pleistocene deposits. This medium to very dense silty sand extends to the maximum investigated depth. This layer includes lenses of very stiff to hard silty clay, at different depths and with varying thickness.

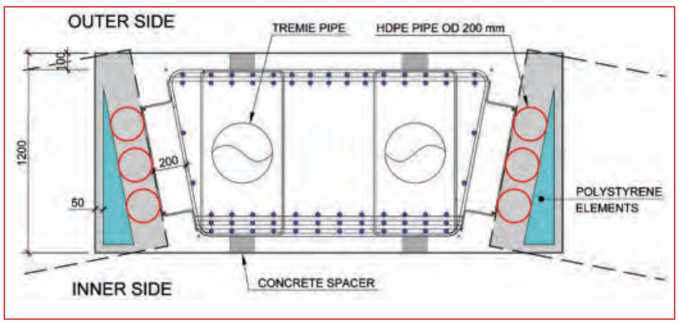
To provide appropriate support for heavy excavation equipment in the working area, a fill that consisted of granular material properly leveled and compacted was executed. Its thickness ranged from about 6.5 to 11.5 ft (2.0 to 3.5 m) on the east side and from 11.5 to 16.4 ft (3.5 to 5.0 m) on the west side of the road tunnel construction site.

## Launching/Reception Shafts Development

The geological conditions of the site led the consortium to install diaphragm walls by using something other than a hydromill,




Tunnel longitudinal profile and plan view which generally ensures better performance in terms of deviations and verticality. The presence of soft clay for about 80% of the excavation depth would have hampered correction of deviation by the milling unit. This would have resulted from the driving flaps penetrating the soft ground instead of rectifying the direction of excavation. Furthermore, given the fine matrix material, the use of a hydromill's drilling wheels and centrifugal pump (which tend to shred and mix soil) would have increased the mud weight. That would have made it difficult to separate the clay from the bentonite.




**Panel's primary cage**

Therefore, the primary panels of the diaphragm walls and barrettes for the shafts were executed using hydraulic grabs. A hydromill was used, however, for secondary panels in order to get proper overlap, ensuring a hydraulic seal and structural continuity for the whole length of the milled joints.

The shafts were multicellular and included five compartments in the launching zone, where TBMs for each tunnel were assembled. The shafts had only two compartments in the reception zone, where TBMs were disassembled. In the launching zone, more space was needed both during the TBM's assembling phase (for back-up and thrust frame installation) and during the excavation phase (for spoil removal, TBM's segments supply, mud supply, etc.).

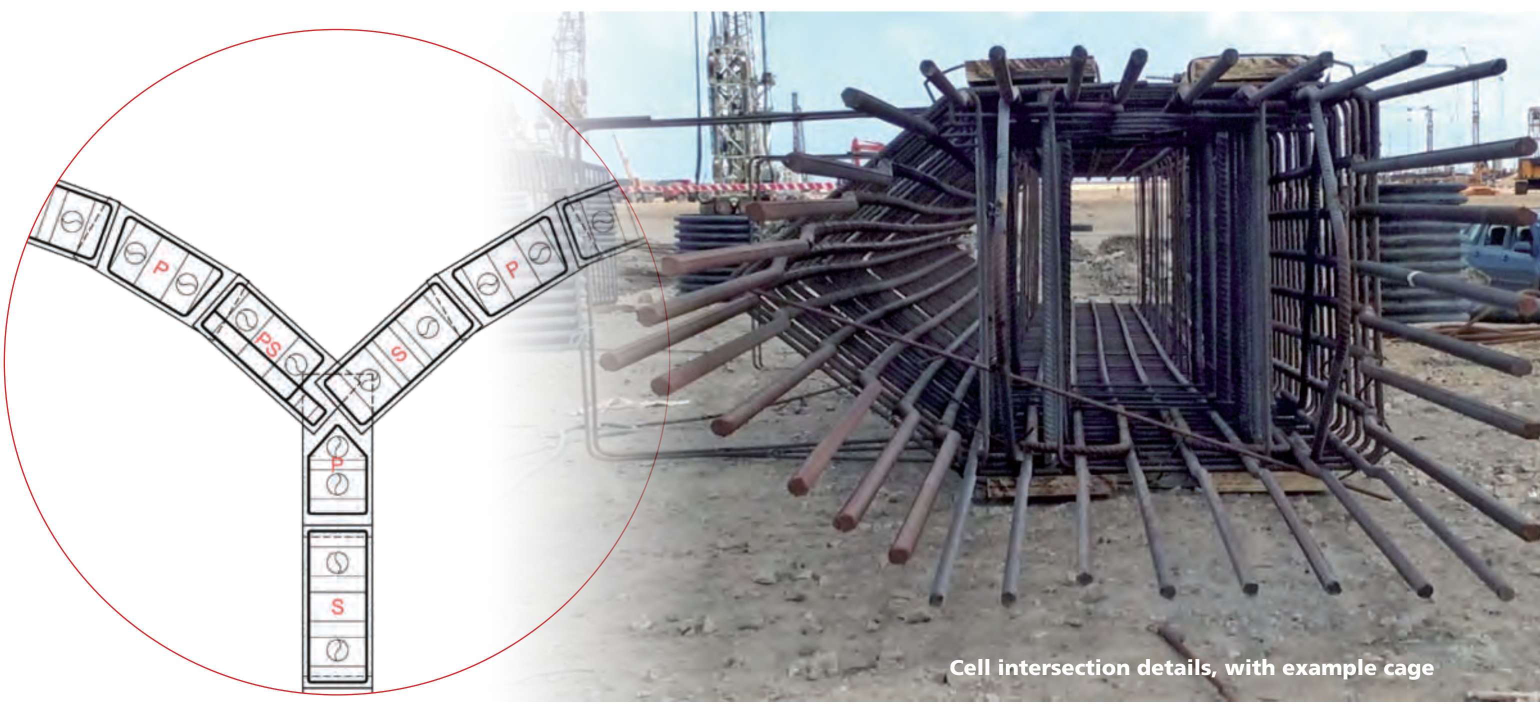
Instead of adopting the classic rectangular form for all shafts, a polycentric shape was developed by intersecting circular shafts, with an inner diameter of 80.4 ft (24.5 m). This geometry chosen by AC-OCI JV took advantage of the arch effect provided by the circular shape of the various sectors of the shafts to allow space within which the TBM could be lowered and assembled, and it permitted excavation up to the maximum design depth without using props or tie rods.

The continuity of the arch effect was obtained by means of diaphragm wall partitions executed in correspondence to the intersections of the circular shafts. Selecting a circular shape to support the structure during excavation produced circumferential stresses on the diaphragm wall. So, special attention was required for excavation verticality controls to ensure that an adequate contact surface existed between the joints of adjacent panels and to limit compressive stresses to a maximum value of 7.5 MPa (1087.8 psi), or 25% of the concrete's characteristic strength.

For the 47 in (1,200 mm) thick shafts' diaphragm walls, Trevi – AC JV opted for 110 in (2,800 mm) long single primary panels, executed by means of hydraulic grabs. Single closing secondary panels with the same dimension were executed with a hydromill able to reach 167.3 ft (51 m) below ground level so panels were embedded at least 9.8 ft (3 m) within the sand formation.

Special attention was paid to the panels placed at the cells' intersecting points, where the perimeter arches converged and where highly concentrated stresses would develop, especially after the demolition of the transversal walls' central part. After analyzing various solutions, single panels reinforced with shaped cages were executed (see below) to not interfere with joint milling.

Isolated diaphragm wall elements (barrettes), 100 in (2,800 mm) long, were added inside the compartments. During the transition phase and throughout the excavation of the tunnel, these barrettes




Cell intersection details, with example cage stabilized the shafts' bottoms against hydrostatic pressure that was applied below the bottom slab. Likewise, the barrettes provided the necessary bearing capacity to the final structure, when the weight of the internal structure and of the backfill became higher than the hydraulic thrust.

For the concrete casting, two tremie pipes were used and positioned symmetrically within the excavation. This approach limited the casting time, produced a better quality and homogeneity of concrete, and ensured a proper rising speed.

## Monitoring Panel Deviations

The absolute necessity to maintain deviations below 0.6% of the depth (±1 to 164 ft [±30 cm to 50 m] to guarantee an adequate wall thickness in correspondence with the joints) required utmost attention while controlling the verticality of the excavation. All the primary panels executed with grab were subjected to verticality controls carried out systematically in the middle and at the bottom of the excavation by means of the Koden ultrasonic system. For secondary panels, a further control was made with the Koden at the bottom of the excavation, in addition to continuous measurements with inclinometers mounted on the hydromill frame. This allowed for reconstructing the panels' real positions and verifying joint contacts before starting the shaft excavation.

## Soil Block

To connect the TBM-bored tunnel and the launching/reception shafts, rigid blocks of consolidated soil were used (called break-in and break-out blocks, where the TBMs started and finished). The rigid blocks consisted of intersecting plastic concrete diaphragm walls.

Soil blocks were executed from many single and multiple panels, which were overlapped 1.1 in (35 cm) so that their larger dimension ran parallel to the tunnel axis. To avoid settlements that would result from consolidation of the soft clay underlying the rigid blocks, 40% of the panels were embedded into the deep sandy layer.

## Shaft Approach Ramps

The approach ramps stretch from the shafts for about 1,362 ft (415 m) on the east side and 1,673 ft (510 m) on the west side. Each of these two structures includes an artificial tunnel in the deepest part that becomes an open-air ramp in the most superficial sections.

The structural diaphragm walls of the longitudinal alignments, which acted as temporary supports during the excavation of the ramps, were developed with 256 in (6,500 mm) long panels with a thickness of 47 in (1,200 mm) in the deepest part of the ramps, and 40 in (1,000 mm) in their most superficial sections.

Regarding excavation depth, the project included 177 ft (54 m) deep panels that were embedded into the underlying sandy layer, alternated with panels whose


Excavation of shaft panel

depth ranged from 121 ft (37 m) to 69 ft (21 m). The two transversal panels adjacent to the deeper panels were also deepened to the sandy layer since they would serve, as the shafts' barrettes do, as foundations for the final structure.

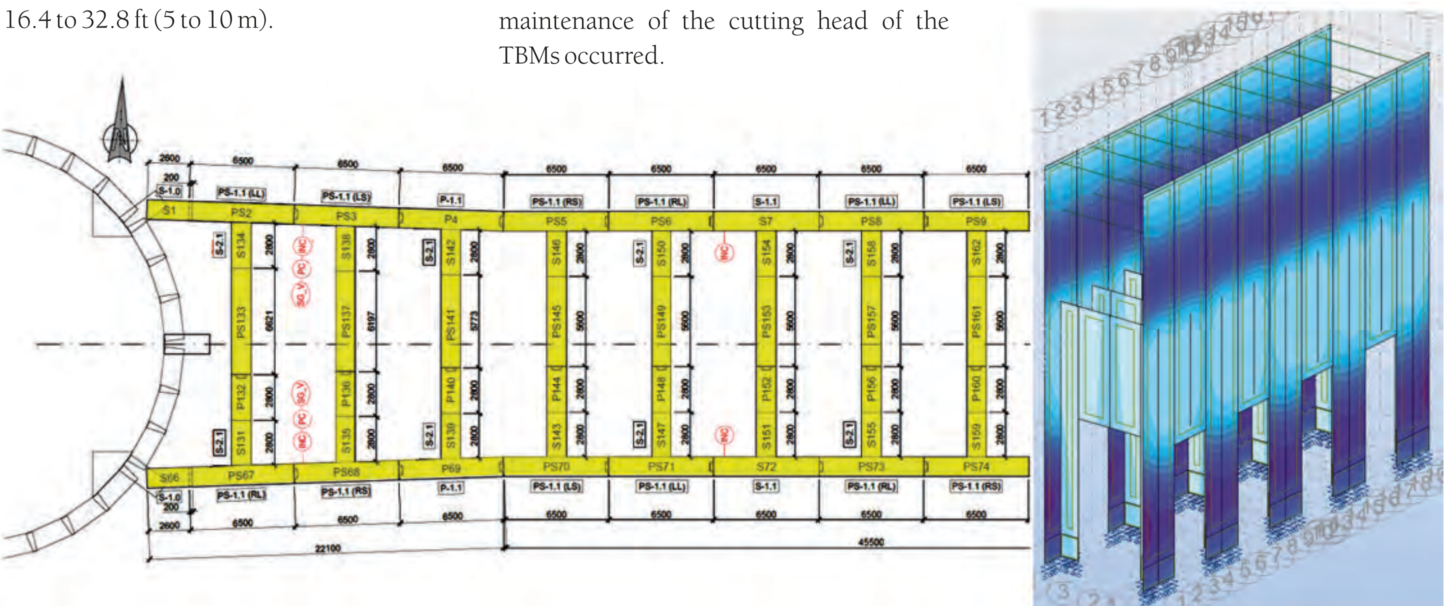
Because soft clay was present at the excavation bottom, the designer developed nonreinforced transverse diaphragm walls that were connected to each longitudinal panel to ensure wall stability. The transverse walls started from the excavation bottom level and extended to a depth of 16.4 to 32.8 ft (5 to 10 m).

three tremie pipes for each multiple longitudinal panel, and two tremie pipes for transverse panels.

## Cross Passages, Safe Havens

Trevi – AC JV also helped build the cross passages and safe havens at the east side of the two tunnels, and the North Safe Haven at the west side. The plan dimensions of the east cross passages were approximately 203.4 ft (62 m) long and 32.8 ft (10 m) wide, expanding to a width of 46 ft (14 m) at the Safe Havens of the tunnels, where maintenance of the cutting head of the TBMs occurred.

with either a grab or the hydromill. The work carried out by Trevi – AC JV for the construction of the North Road Tunnel involved 194,680 $yd^2$ (163,000 $m^2$) of structural diaphragm walls for the launching/reception shafts, as well as the east and west cut and covers. All told, 103,550 $yd^2$ (86,600 $m^2$) of plastic diaphragm walls were built to develop the east and west soil blocks, cross passage CP6 and safe havens, plus the north haven at cross-passage CP2.



**Approach ramp plan and 3-D view**

## Construction Machinery

The sequencing of primary panels, follower panels and secondary panels allowed all to be executed with hydraulic grabs (except transverse closing elements). The connection joint was developed using steel sheet piles. The hydromill was employed for the transverse closing panels, since good contact was required between them and the longitudinal diaphragm wall. This approach required designing special reinforcement cages for the diaphragm walls. This resulted in a recess within the central portion, so as to avoid the milling of bars, in case of possible deviations of the transversal panels; in this way, the structural integrity of the longitudinal elements was preserved. In this case, the concrete casting of the panels was carried out using

The dimensions of the West Cross Passage were approximately 164 ft (50 m) long and 15 ft (4.6 m) wide. Only the North Safe Haven, 57.4 ft (17.5 m) long and 15 ft (4.6 m) wide, was part of Trevi's scope of work.

Like the break-in and break-out blocks, the soil for the cross passages was consolidated by using intersecting plastic concrete diaphragm walls; the single and multiple panels overlapped by 1.1 in (35 cm) to ensure a proper hydraulic seal during tunnel excavation. The soil improvement depth varied from approximately 167 ft (51 m) to 169 ft (51.5 m), according to the tunnel's depths.

## Conclusion

The project primarily involved constructing diaphragm walls, consisting mainly of multiple-bite panels excavated

A unique aspect of the work was the use of plastic concrete blocks instead of jet-grouting blocks for soil consolidation at the break-in/break-out and cross passages. This was due to equipment availability for the plastic blocks from diaphragm wall development.

The work was performed in about 35 months, ending in December 2017. After the diaphragm development work, the remaining structures were excavated as planned, and on schedule.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