A Greater Wonder

The Panama Canal expansion project features new lock complexes on the Atlantic and Pacific sides of the waterway, each with a series of water-saving basins.

COURTESY OF THE PANAMA CANAL AUTHORITY

Often considered the eighth wonder of the world, the Panama Canal now has a third lane with its own set of locks that has doubled the waterway's capacity and increased the size of vessels that the canal can accommodate. The $5.25-billion expansion project has also sent infrastructure improvement ripples around the globe.

By Robert L. Reid

WHAT CAN ENGINEERS do to make a "wonder of the world" even more remarkable?

When the question involves the Panama Canal, an achievement often dubbed the eighth wonder of the world, the answer encompasses a series of international engineering efforts that recently expanded the canal, doubling its capacity and inspiring additional infrastructure improvements around the globe.

The original portion of the canal, constructed by the United States between 1904 and 1914, enables ships to pass between the Atlantic and Pacific oceans across the 80 km wide Isthmus of Panama. It has two sets of locks on both the Atlantic and Pacific sides, along with a navigation channel through Gatun Lake and the Culebra Cut (also known as the Gaillard Cut), a flooded valley that was excavated through the continental divide as part of the original canal construction. The locks are adjacent to each other, enabling ships traveling in opposite directions to pass. The three chambers of each lock complex raise or lower the vessels 26 m in steps to accommodate the difference in elevation between the ocean-level entrances and Gatun Lake, the artificial body of water created inland on the Atlantic side as a reservoir for the canal. (Read "Between Two Oceans: The Panama Canal," *Civil Engineering,* July/August 2014, pages 42–45.)

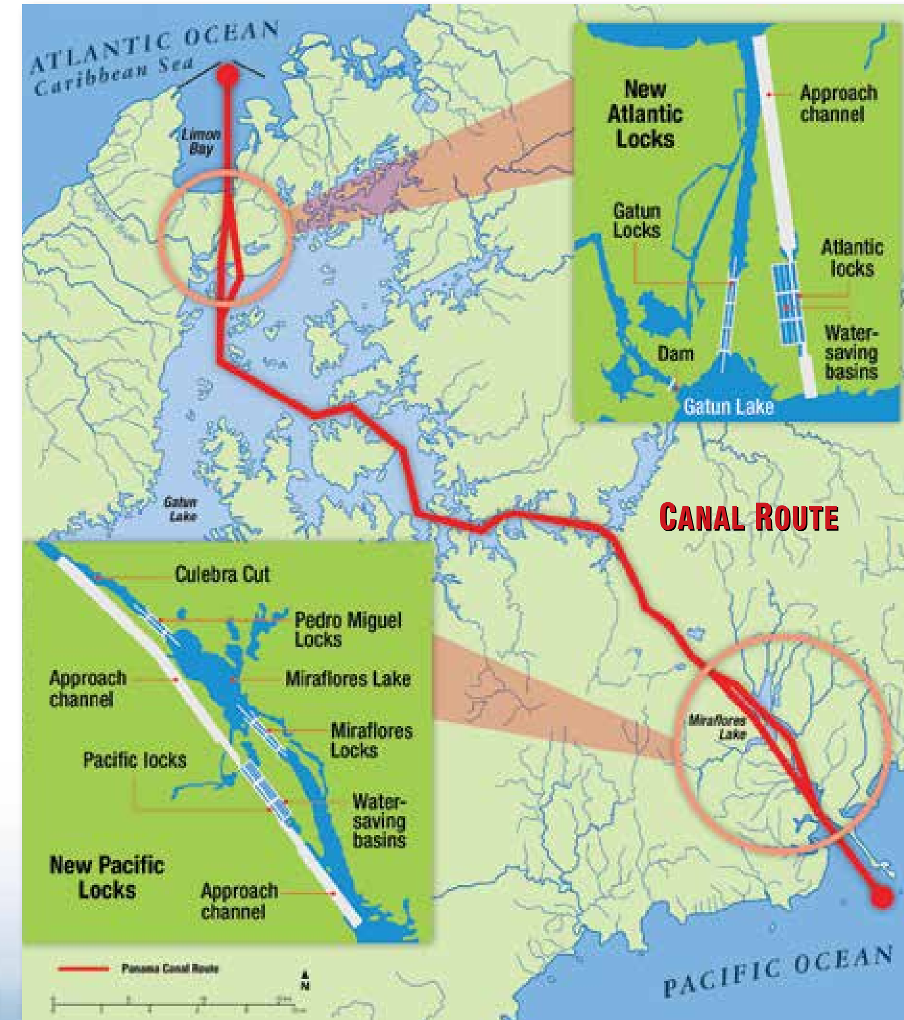
Although owned and operated by the United States for more than eight decades, control of the canal reverted to Panama by treaty in 1999. Construction work on the $5.25-billion expansion project, which was overwhelmingly approved by Panamanian voters in 2006, began in September 2007 and was completed in June 2016. The new project is designed to augment the original system, which remains in operation.

The centerpiece of the expansion was the construction of a third set of locks with chambers that are larger than the 1914 lock complexes in order to accommodate modern container ships and other types of vessels that are too large to traverse the original canal. Located close to but separate from the original lock complexes, the new locks again feature three stepped chambers on the Atlantic and Pacific sides, providing a single, wider lane for transit. The project also includes an innovative series of water-saving basins. Each of the new lock chambers also features a pair of rolling gates at each end that open and close laterally, in contrast to the miter gates on the original locks, which swing open and closed.

The project also involved the construction of a new, 6.1 km long access channel for the new locks on the Pacific side of the canal so that ships using the new locks can bypass Miraflores Lake, an artificial lake that feeds into the original lock complex on the Pacific side. In this way ships can make their way directly to the Culebra Cut. Because the elevation of the water in this access channel will be as much as 9 m higher than the water level in Miraflores Lake, four structures similar to very tall levees and referred to as the Borinquen Dams also were constructed on either side of the new channel to control the water levels and prevent leakage.

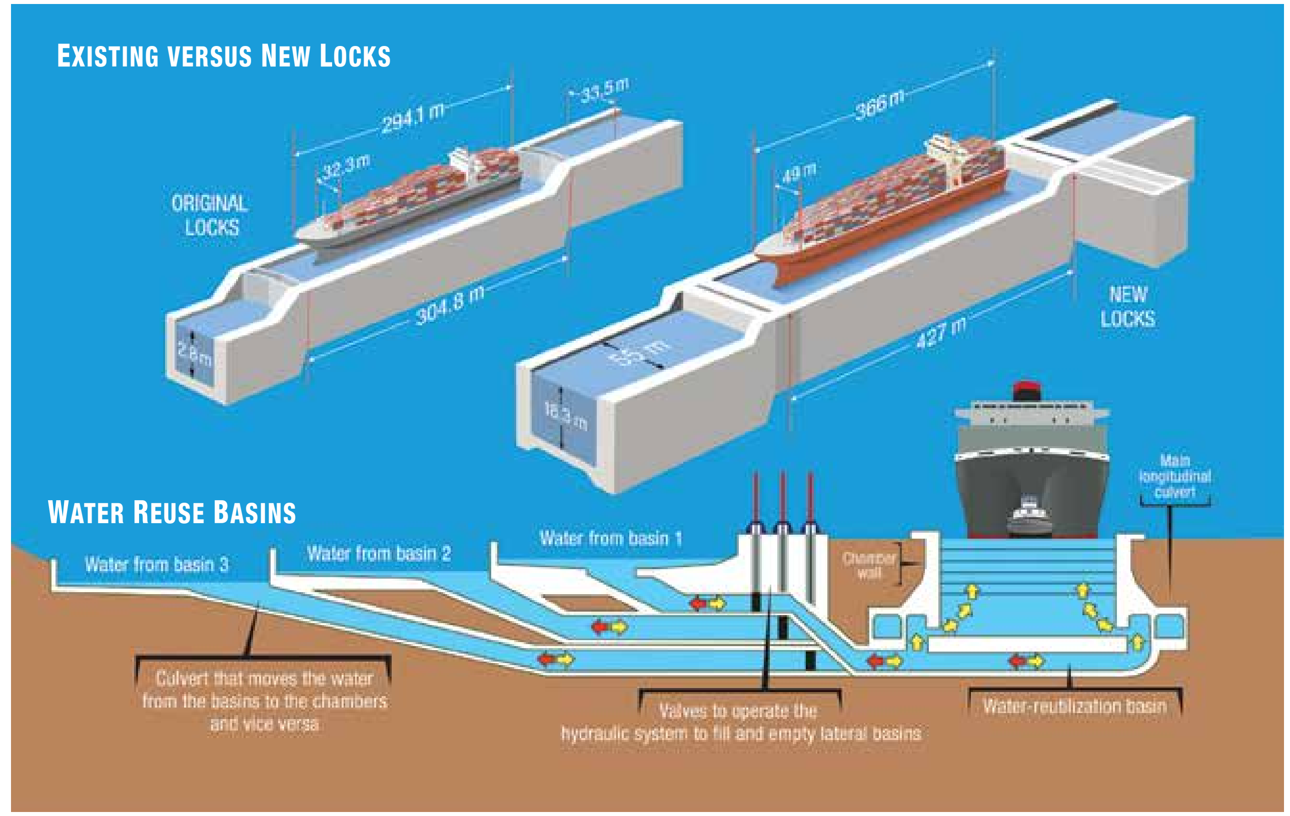
Improvements were also made to the canal's navigation channel by dredging millions of cubic meters of material from the ocean-level entrances, from Gatun Lake, and from the Culebra Cut (see "Wider and Deeper," page 55). The spillways and gates at Gatun Dam, as well as other infrastructure at Gatun Lake, also were modified to accommodate the raising of the maximum operational level of the lake by 45 cm to improve the canal's water supply and draft (see "Raising Gatun Lake," page 56).

The expansion project was constructed under a design/build contract worth $3.2 billion that was awarded by the Panama Canal Authority, or ACP (Autoridad del Canal de Panamá), the agency in Panama that operates and maintains the canal, to an international consortium known as Grupo Unidos por el Canal,



COURTESY OF THE PANAMA CANAL AUTHORITY, *BOTH*

The new locks are larger than the original (1914) ones to accommodate massive modern vessels.



COURTESY OF THE PANAMA CANAL AUTHORITY, ALL THREE

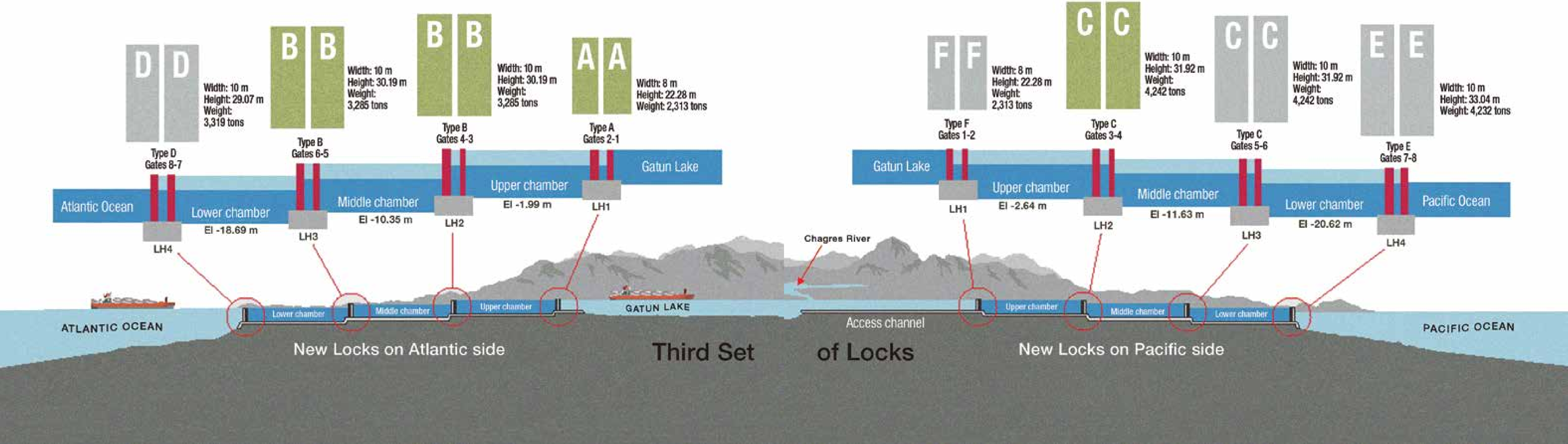
SA. The consortium was led by Salini Impregilo S.p.A., of Milano (Milan), Italy, and included Sacyr Vallehermoso, S.A., of Madrid, Spain; Jan De Nul NV, of Aalst, Belgium; and Constructora Urbana, S.A., of Panama City.

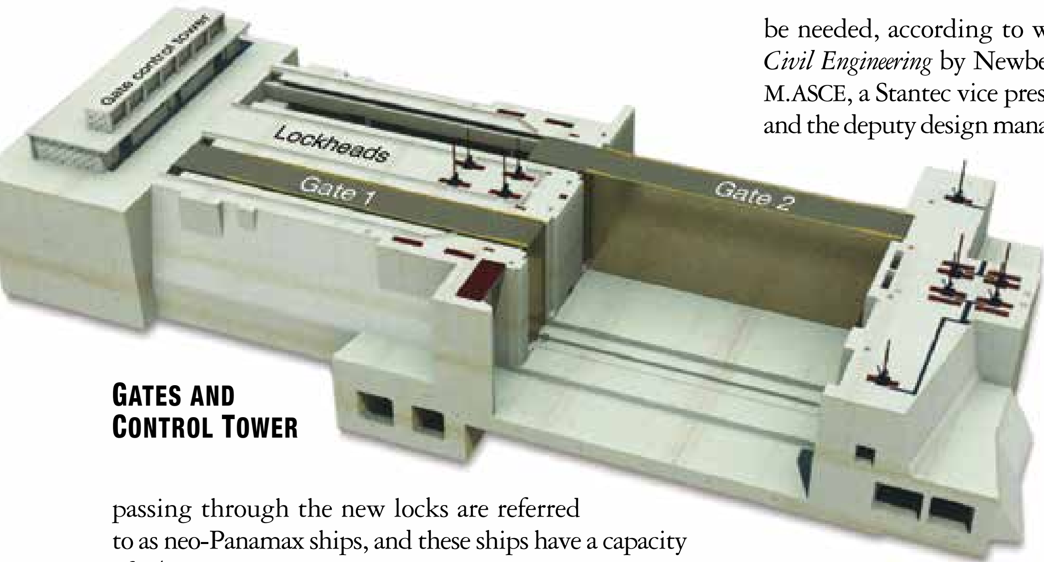
Designed and constructed by an international team of engineers and builders, the new locks are the $3.2-billion centerpiece of the $5.25-billion expansion project.

The new locks were designed by Consultores Internacionales del Canal de Panamá, LLC, a joint venture led by the international engineering firm MWH Global, now part of Stantec, with partners Tetra Tech, Inc., based in Pasadena, California, and Iv-Groep b.v., based in Papendrecht, the Netherlands.

Among the numerous other consultants involved in the expansion project were Dredging International NV, part of DEME, of Zwijndrecht, Belgium, which was responsible for the dredging to widen the Pacific entrance (Jan De Nul dredged the Atlantic entrance); Cimolai Technology SpA, of Carmignano di Brenta, Italy, which fabricated the gates for the new locks; and Hyundai, of South Korea, which fabricated the filling and emptying system valves. The international consortium in charge of a crucial phase of the Pacific access channel included FCC, of Madrid, Spain; ICA, of Mexico City; and the San José, Costa Rica, office of Constructora MECO SA. Various departments within the engineering division of the ACP also were responsible for key aspects of the expansion project.

The original Panama Canal locks are 33.5 m wide and 304.8 m long and provide an operating water depth of 12.8 m. By comparison, the new locks are longer, wider, and deeper, measuring 427 m in length, 55 m in width, and featuring an operating water depth of 18.3 m, according to information from the ACP. The largest vessels capable of transiting the original locks are known as Panamax ships and have a capacity of 4,400 twenty-foot equivalent units (TEUs), the typical shipping containers that fill the cargo holds and are stacked on the decks of these vessels. The largest vessels capable of





GATES AND CONTROL TOWER

passing through the new locks are referred to as neo-Panamax ships, and these ships have a capacity of 14,000 TEUs.

Even after the construction of the new locks, some vessels will still be unable to use the canal, notes Mike Newbery, P.E., a vice president in Stantec's Chicago office and the design manager for Consultores Internacionales del Canal de Panamá. These ships, dubbed post-Panamax vessels, include some of the largest supertankers, but in any event they tend not to follow the trade routes that use the canal, Newbery adds. To make the new locks large enough to accommodate every vessel afloat would have made the expansion project even more expensive and required even more water for operating the system, he explains. The locations of the new lock complexes "were selected to provide sufficient real estate for expansion" should an even larger, fourth set of locks ever be needed, according to written information provided to *Civil Engineering* by Newbery and Nick Pansic, P.E., D.NE, M.ASCE, a Stantec vice president in the firm's Chicago office and the deputy design manager for Consultores Internacionales del Canal de Panamá's Chicago design center.

Stantec has been involved with various work at the Panama Canal since the late 1990s, developing feasibility studies and supporting studies, conducting conceptual work with such other international engineering firms as Parsons Brinckerhoff, now part of WSP, to develop a master plan, and performing other work, all of which eventually led to the design of the third set of locks, notes Newbery. At the peak of Consultores Internacionales del Canal de Panamá's efforts, more than 400 engineers located in offices on three continents were working on elements of the expansion project either full-time or part-time, Newbery adds. Moreover, Stantec and its partners managed to keep the same team in place from 2007 until completion, a "continuity that was very, very powerful in providing the right design, the right quality to the project," Newbery says.

From an initial list of 24 potential sites for new lock complexes, Stantec and the ACP gradually reduced the candidates to just 6 (3 for the Atlantic side and 3 for the Pacific side) before making the final selections. Ultimately, the

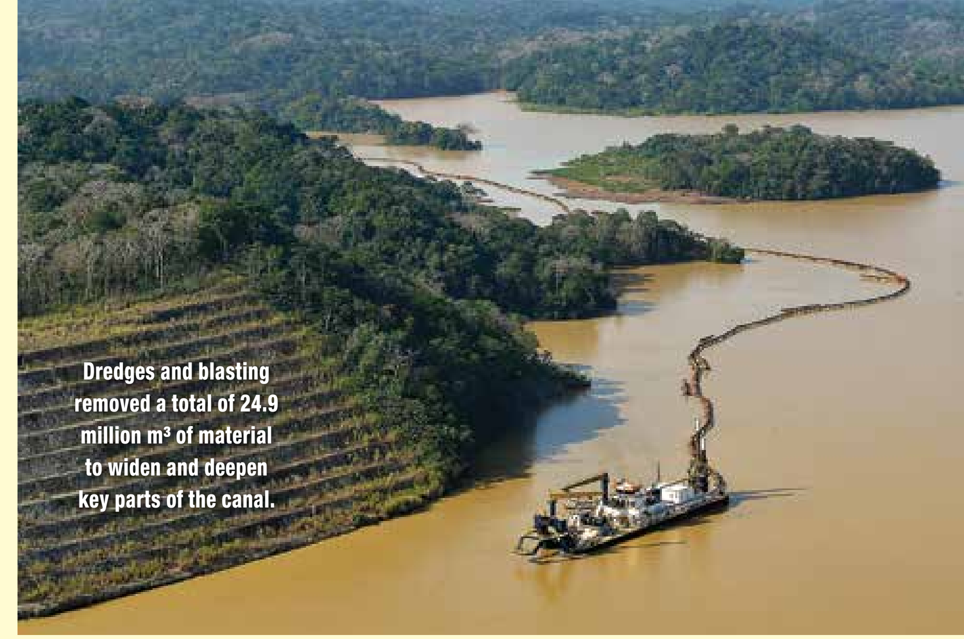
The new lock chambers each feature a pair of rolling gates at each end that open and close laterally.

COURTESY OF THE PANAMA CANAL AUTHORITY, ALL THREE

WIDER AND DEEPER

BY LUIS SANTANACH BERNAL

A key component of the recent Panama Canal expansion involved the widening and deepening of Gatun Lake, the artificial lake that serves as the canal's reservoir, and the deepening of the Culebra Cut (also known as the Gaillard Cut), a flooded valley created during the original construction of the canal to connect Gatun Lake to the lock complexes on the Pacific side. The work covered approximately 50 km of the waterway within the freshwater portion of the Panama Canal.



Dredges and blasting removed a total of 24.9 million m³ of material to widen and deepen key parts of the canal.

A total of 24.9 million m³ of material was removed via earthwork, land dredging, and dredging operations, and the effort was supported by drilling and blasting operations both underwater and on land. What is more, 34 steel-framed range light towers were constructed to improve navigation safety along the waterway.

The main equipment for this work included two drilling and blasting barges, four cutter suction dredges, four mechanical backup dredges, one trailing suction hopper dredge, one mechanical dipper dredge, and one clamshell dredge, the last used for shoal chasing. Five of the dredges belonged to the Panama Canal Authority, or ACP (Autoridad del Canal de Panamá), the agency in Panama that operates and maintains the canal; the other six were owned by dredging companies.

Of the 20 reaches within the canal that were dredged, 17 were part of the original canal and 3 were associated with the third set of locks. The sites were dredged to a minimum depth of 9.14 m with respect to the precise level datum (PLD) with a dredging tolerance to 8.53 m PLD. (Panama Canal elevations are measured in relation to a particular point, the PLD, which corresponds to 0.3 m below the average sea level at the Pacific entrance and 0.06 m below the average sea level at the Atlantic entrance.)

A minimum channel width of 218 m also was established. But since the reaches are as much as 304 m wide at Gatun Lake, the slope design was reviewed with respect to the type of soil and rock encountered in a particular area. The channel design was performed by the civil, geotechnical, and structural branches of the ACP engineering division and by an ACP dredging team. The range light towers were designed by the ACP's civil and structural branches with the support of the geotechnical branch and other ACP offices.

The contract to widen and deepen the northern reaches of Gatun Lake was awarded to Dredging International, part of DEME, based in Zwijndrecht, Belgium. This work started in June 2010 and was completed in March 2012. A cutter suction dredge, a hopper dredge, and a backup dredge were used to excavate 4 million m³ of material. Underwater drilling and blasting operations also were performed over a period of less than one month. The major challenges during this work included the following:

- Removal of old equipment from the bottom of the canal: Some 171 diving operations were required to lift out pieces of railroad tracks and equipment that had been used during the original construction of the waterway (between 1904 and 1914). The diving included hoisting operations at night carefully coordinated with the canal's marine traffic control office to ensure the safety of the divers and other personnel aboard the work boats.
- Land reclamation: The material taken from De Lesseps Island in the Chagres River, which was dammed to create the Gatun Lake reservoir, amounted to 1.4 million m³. This was added to nearby Orquídea (Orchid) Island, which is less centrally located in the navigation channel.
- Dredging the hardest rock encountered during the Panama Canal expansion project: In places the dredges had to cut through gabbro, an intrusive igneous rock with an estimated unconfined strength of 125 MPa.

In the new reach in the northern section of the canal called Cartagena, a total of 3.8 million m³ of material was removed through earthwork and dredging performed by Jan De Nul NV, of Aalst, Belgium. The work began in August 2010 and ended in November 2012. As mentioned above, drilling and blasting from the land and underwater were performed. Earthwork equipment was used to remove the upper part of the material, and the remainder was dredged using a cutter suction dredge.

To widen and deepen the southern reaches in Gatun Lake, the ACP relied on its own dredging division, which ultimately removed a total of 13.4 million m³ of material while also dredging 15 km of channel. These endeavors began in March 2007 and ended in December 2015. The ACP also contracted for two charter dredges owned by Jan De Nul and by Royal Boskalis Westminster N.V., of Papendrecht, the Netherlands.

The deepening of the Culebra Cut required the removal of a total of 3.2 million m³ of material by the ACP's dredging division between October 2007 and December 2013. The major challenge here involved the fact that the Culebra Cut is the narrowest and most curved section of the canal. So this work had to be carefully planned and performed so that it would not interfere with canal transits.

Two contracts were awarded for the construction of the 34 range light towers. The first, for eight towers, was awarded to SEMI S.A., of Madrid, Spain. The other was granted to Ingeniería Continental, S.A. (ICONSA), of Panama City, for the remainder of the structures. The latter contract included the installation of three towers located on a platform supported by piles that were driven by the floating crane of the ACP's dredging division. For the most part, three main types of foundations were used for the towers: Micropiles supported the towers located along the banks of the canal. Large shallow foundations were used for the towers that could be accessed via roadways, and steel pile foundations were used for the towers that were located over the water. ICONSA designed the micropile foundations, and the ACP's engineering division designed the other systems.

Luis Santanach Bernal, an engineer and water manager for the Panama Canal Authority's Pacific water sector, was a project manager during the expansion project.

new lock complex on the Atlantic side was constructed about half a mile to the east of the original locks; the new Pacific complex is located about half a mile to the southwest of the original locks.

Although the two new complexes operate identically, there were considerable differences in the design and development of each site on the basis of such factors as geotechnical conditions, potential seismic loading, and ocean tidal elevation ranges. For example, the Atlantic side features soft rock from the Gatun Formation that is easy to excavate but decomposes when exposed to water. The excavation for the new access channel on that side encountered what is called Atlantic muck, an organic material with a consistency similar to that of toothpaste. On the Pacific side, however, the rock included basalt, which required blasting prior to excavation, as well as a softer rock (La Boca Formation) and Pacific muck. There were also several geological faults that crossed the Pacific locks complex and approach channels, which meant that seismic loads governed the design of the locks structure there. In fact, an active fault runs right beneath the Pacific side approach channel and the Borinquen Dams lining the channel and passes close to the lock complex itself. As a result, the Borinquen Dams were designed to withstand a seismic acceleration of 0.98*g*, and the lock complex was designed to withstand an acceleration of 0.72*g*.

Several geological faults crossed the Pacific locks complex and approach channels.

By contrast, the potential seismic loads on the Atlantic side, while large, are only two-thirds as great as on the Pacific side and did not govern the structural design.

Other differences between the new lock complexes involve the ocean tides at the canal entrances. On the Atlantic side, the design tidal range is approximately ±0.3 m, while on the Pacific side it is an order of magnitude greater, exceeding ±3.0 m. This meant that the lock complexes on the Pacific side required deeper excavations, higher lock walls, larger approach structures and fender systems, and larger systems overall, including slightly larger water-saving basins to accommodate the greater tidal ranges.

Even the rainfall differs from one side of the isthmus to the other, averaging approximately 2.5 m per year on the Atlantic side but just 1.7 m per year on the Pacific side. Construction on the Pacific side also required the design and construction of a 2 km long cofferdam to isolate the lower chamber area from the Pacific Ocean. No actual cofferdam was needed for the Atlantic locks because they were constructed just downstream of Gatun Lake at a site that dated to an expansion project that was begun in 1939 but never completed. That site already had a barrier separating it from Gatun Lake

Raising Gatun Lake

By Miguel Lorenzo

Raising the maximum operating level of Gatun Lake was one of the four main undertakings of the Panama Canal expansion project. Its goal was to increase the storage capacity for water used for human consumption and other necessities as well as for the operations of the expanded Panama Canal. This effort makes it possible to raise the maximum operating level of Gatun Lake by roughly 45 cm, from the current elevation of 26.67 m with respect to the precise level datum (PLD) to 27.13 m PLD. (Panama Canal elevations are measured in relation to a particular point, the PLD, which corresponds to 0.3 m below the average sea level at the Pacific entrance and 0.06 m below the average sea level at the Atlantic entrance.)

The increase in the maximum operating capacity of Gatun Lake equates to an additional storage capacity of about 200 million m³ of water, which would make possible about 1,100 additional transits each year. The undertaking had three main aspects: reservoir impoundment elements, operational efficiency, and damage prevention efforts.

The reservoir impoundment elements were aimed at securely containing the water of Gatun Lake up to the new desired level. The lake includes a dam that features a series of 14 sliding spillway gates that were extended as part of the project to raise the lake's operating level. The project also involved work on 32 miter gates in the Pedro Miguel Locks, located south of the Culebra Cut (also called the Gaillard Cut), and in the Gatun Locks, located north of Gatun Lake, both sets of locks being part of the canal's original facilities. These original locks feature swinging miter gates, in contrast to the sliding gates of the new locks constructed during the expansion project. The older locks also feature locomotives that assist the ships through the lock chambers; ships transit the new, third set of locks with the assistance of tugs. Complicating matters, the work had to be carried out while the canal remained in operation; there were no redundant or replacement systems for these elements of the canal's infrastructure.

The miter gates of the original locks are opened and closed by hydraulic cylinders. As part of the project to raise the lake's operating level, new hydraulic cylinders featuring semisubmersible technology were installed, and flexible rubber grommets and screens were fabricated and installed to isolate the cylinders. Moreover, the connection of a yoke, which supports part of the miter gate system, was sealed, and the gates' miter seals were extended. Furthermore, all of the openings below 27.43 m PLD in the machinery rooms at the upper level of the Pedro Miguel and Gatun locks had to be sealed.

To ensure operational efficiency and safe transits through the Pedro Miguel and Gatun locks at the new water level included the following:

- Isolation of the slots for the electrical conductors that power the locomotives;
- Relocation of the electrohydraulic systems of the miter gates and the isolation of the locks' machinery tunnel by watertight doors in the hydraulic cylinder rooms of the miter gates;
- Installation of new, semisubmersible water-level sensors;
- Improvement of the ventilation system of the machinery tunnel in both locks.

These efforts also addressed the operations of the Gatun Dam spillway, a major component of the system for regulating the canal's water resources, via the construction of two extended-height floating caissons. These caissons are used for performing spillway gate

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New, extended spillway gates were installed on the dam at Gatun Lake.

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maintenance. Two new sliding gates with extended heights were also fabricated to serve as spare gates.

The damage prevention aspect included preservation work focused on such canal facilities as piers, raw water intakes, and miscellaneous structures, as well as protecting and adapting other structures on private property that would be affected by the new maximum level of Gatun Lake. (Eligibility for private property remediation was determined on the basis of socioenvironmental criteria established by the Panama Canal Authority, or ACP [Autoridad del Canal de Panamá] for the expansion program.)

The damage remediation work involved 18 ACP infrastructure and operating facilities. Provisions were made to mitigate any effects on the facilities' operations or regular functions. The ACP was required to work closely with the potentially affected operating units, carry out topographic and bathymetric studies, conduct research, and construct and test prototype components. The proposed solutions had to consider the long-term reliability of each component.

Since much of this work involved the most critical infrastructure of the canal and was complex and highly specialized, the ACP chose its own engineers and other experts to complete these projects. A balance was struck between this new work and the regular functions of the ACP's employees, who maintain and operate the canal. The project also accommodated budgetary limits; strict quality controls; and standards relating to the environment, safety, transparency, and accountability.

One of the first steps was developing detailed engineering designs for all major components. These designs were developed through well-documented review processes to ensure functionality, economy, and constructability while minimizing effects on the regular operation of the system. The development of these designs involved support from various disciplines and departments and covered aquatic and air logistics, state-of-the-art technology for earth and hydrographic surveying, community engagement and interagency coordination, the study and evaluation of historical documentation, and extensive market surveys and interviews with world-class manufacturers and consultants. The ACP's engineering division was a key player in these efforts, along with its operational hydrology unit and environmental management and monitoring section, among others.

A series of tests involving prototypes of the major systems began in October 2009 with a prototype of the proposed new hydraulic cylinders with semisubmersible technology for the locks' miter gates. Additional prototype tests were carried out for the mechanical assembly designed by the ACP's mechanical engineering section that would seal the gate yoke connections, as well as the miter seal extension of the gates. Tests were also run on water-level sensors with commercial semisubmersible technology that would replace existing technology, thus ensuring the required functionality of the system under the new maximum operating level.

All of the impoundment elements and the operational elements were executed by ACP personnel, except for the improvements to the ventilation system and the installation of bulkheads and watertight doors intended to isolate the lock machinery tunnels, which were assigned to local contractors. This scheme made it possible to carry out work of greater technical complexity without affecting the reservoir capacity or ship traffic.

The remediation of more than a dozen operational infrastructure systems for the canal involved work on boat docks, fueling docks, and raw water intakes, as well as on public boat ramps, a pilot dock, and tug and launch landing locations.

The remediation work on private property in remote areas and areas difficult to reach on the shores of Gatun Lake was assigned to both ACP personnel and local contractors. These efforts included the relocation of three houses, adjustments to other houses, and upgrades to docks, community structures, and parish facilities.

Once completed, these various efforts made it possible to increase the maximum operational level of Gatun Lake to accommodate the new hydraulic demands of the expanded canal.

Miguel Lorenzo is an engineer and executive manager in the Panama Canal Authority's engineering division.

as well as a natural "cofferdam" of unexcavated material separating it from the Atlantic Ocean.

The 1939 undertaking played another role in the expansion project. On the Atlantic side, the alignment of the new set of locks matched the alignment of the locks proposed in 1939. As a result, the construction of the new lock chambers took advantage of the existing excavation, widening and deepening that space and constructing the water-saving basins there adjacent to the earlier work, Newbery notes. But on the Pacific side, to bypass Miraflores Lake, the 2016 alignment differed from that of 1939. This meant that roughly two-thirds of the footprint of the water-saving basins on the Pacific side had to be constructed atop the 1939 excavations. Thus, the elevation of the site for the Pacific basins was now too low, Newbery says. The solution involved cleaning out the site, backfilling it with rock up to a certain level, and then adding a finer material above that to bring the land to the appropriate elevation for the new basins, Newbery explains.

The nine basins at the new lock complexes are each approximately 70 m wide, 5.5 m deep, and 407 m long. As noted previously, they are slightly larger on the Pacific side but generally match the length of the chambers they help to fill and empty. The basins feature a thick polyvinyl chloride liner for waterproofing, along with a system of underground drainage pipes and filters to collect any water that seeps through the liner. The underground systems are also designed to prevent water pressure from raising the liner when the basins are dewatered for maintenance, Newbery adds.

To assist with the complicated seismic and hydraulic analyses and other studies that the canal expansion required, Stantec turned to the supercomputers in its Chicago office and to SIMULIA, which is headquartered in Johnston, Rhode Island, and is part of Dassault Systèmes. The models of the lock heads, which house the chambers' rolling gates, involved a total of 224 central processing units from several different sites and as much as 100 hours of computer running time, "which we believe is unprecedented in our industry," Newbery notes.

Stantec's office in Buenos Aires, Argentina, also conducted numerous numerical hydraulic model studies, and a 1:30 scale physical model of the new lock chambers was constructed at a laboratory belonging to CNR, which is headquartered in Lyon, France. Measuring 60 m long and 10 m wide, the physical model featured scale models of vessels that were tested in the model lock chambers. The latter were operated with three model water-saving basins to test the filling and emptying of the chambers as well as the key forces that would be exerted on the hulls of the ships.

"We used all these models to analyze the various aspects of moving water from Lake Gatun through the culverts and conduits into the lock chambers and back out again to the water-saving basins to make sure we could meet the very stringent filling and emptying requirements," explains Newbery. The modeled hydraulic performance of the new locks and basins was later confirmed with measurements during the commissioning of the locks (see "Testing the New Locks," below).

The various systems for filling and emptying the new chambers require 7 percent less water than the original chambers.

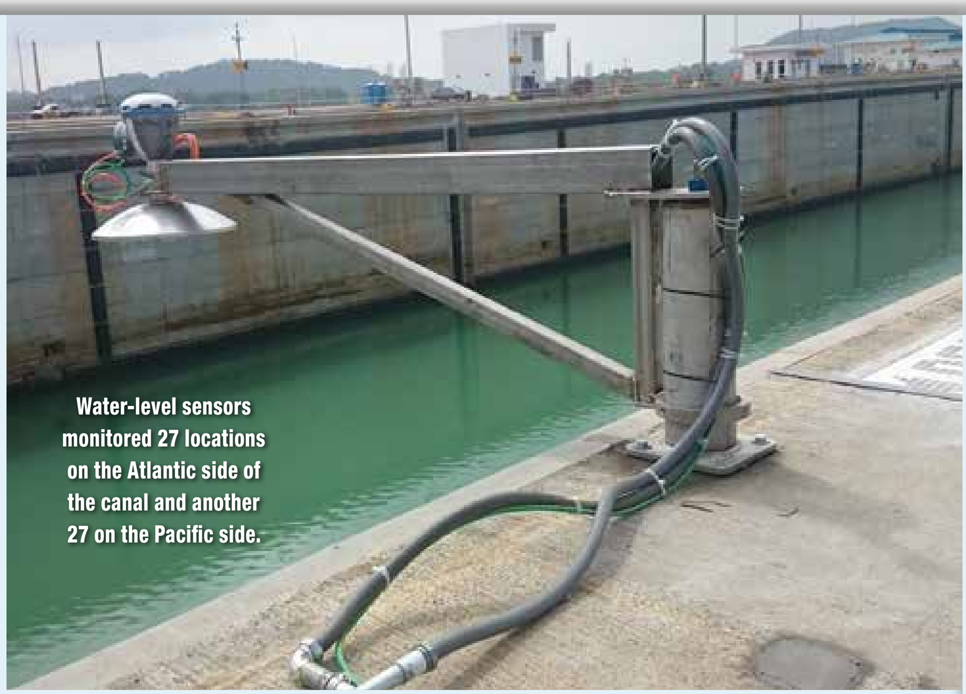
Stantec also worked closely with Autodesk, Inc., of San Rafael, California, to produce facilities information management (FIM) models for clash detection studies involving the mechanical and electrical systems, as well as other aspects of the expansion project. Overall, "this was the largest application of FIM modeling on a major civil works project," Newbery says, and the design team used those modeling tools "on a larger scale than had ever been done before."

The new lock chambers are constructed of concrete and are as much as 30 m deep, the walls approximately 2 m thick at the top. From there they slope down to a base roughly 20 m wide to accommodate the two water-conveying culverts located on each side of the chambers. Relying on gravity, the main culvert draws water from Gatun Lake, whereas the auxiliary culvert, which is linked to the main culvert, distributes water into the lock chambers and also draws water from the adjacent water-saving basins. The main culvert is more than 8 m wide and approximately 6.5 m tall. Unlike the 1914 lock chambers, which are filled and emptied through openings in the floor of the chamber, the new lock chambers feature a side-filling system with a series of 20 ports in each of the lock chamber walls. Altogether, the various systems for filling and emptying the new chambers require 7 percent less water than the original chambers, even though the new chambers are considerably larger.

The 16 rolling gates that close off the 55 m wide lock chambers are massive steel-framed structures. There are three types in each lock complex, and they are arranged in

Testing the New Locks

By Norman F. Perkins, P.E., M.ASCE, Daniel Gessler, Ph.D., P.E., D.WRE, M.ASCE, and Philip S. Stacy



Water-level sensors monitored 27 locations on the Atlantic side of the canal and another 27 on the Pacific side.

ALDEN RESEARCH LABORATORY, INC.

The recently completed third set of locks at the Panama Canal incorporates several civil components and hydraulic design features that are intended to reduce routine maintenance and conserve water. For instance, rather than relying on the locomotives used in the original locks, the ships transit the new locks with assistance from tugboats. Water-saving basins are used to reduce the freshwater requirements from Gatun Lake. While these efforts confer important benefits, they also present various hydraulic challenges that can affect not only the number of ships passing through the canal, which is limited by the speeds at which the lock chambers are emptied and filled, but also the water surface stability during the emptying and filling of the chambers.

As part of the commissioning phase of the new locks, the key hydraulic parameters associated with these challenges were tested over a 10-week period by a so-called performance team consisting of Alden Research Laboratory, Inc., of Holden, Massachusetts; Cameron, part of Schlumberger; Flowmeter Service, of Northampton, Massachusetts; and Rennasonic, Inc., which has offices in East Falmouth, Massachusetts, and Naples, Florida.

Prior to the design and construction of the new locks, the Panama Canal Authority, or ACP (Autoridad del Canal de Panamá), developed a set of requirements that defined the performance characteristics that the locks would have to meet. These specifications included maximum allowable filling times, maximum allowable water surface slopes in the locks, maximum allowable velocities in the culverts and conduits, and required water conservation. These requirements were critical to the success of the new locks because slower filling times than expected would reduce the number of lockages per day, while velocities higher than allowable could lead to a deterioration of the concrete lock structure. Excessive water surface slope in the locks can increase the force required to restrain a vessel during lockage. Other limiting hydraulic parameters are no cavitation, no air entrapment, and no water hammer (which refers to abrupt and potentially damaging increases in water pressure when a valve is opened or closed), and maximum water velocities were established in the lock approach channel. Water conservation is also critical to minimize the environmental effects of the canal operations.

To verify compliance with these requirements, the performance team and the international consortium known as Grupo Unidos por el Canal, SA, which held the design/build contract to construct the new locks, installed and monitored a series of sensors and other measuring devices throughout the lock complexes:

- Twelve temporary water-level sensors that were accurate to within 0.5 mm were installed in the lock chambers (six in the Atlantic locks and six in the Pacific locks). The sensors measured the water surface slope during the filling of the chambers, as well as the water level in the chambers, so that the flowmeters could be calibrated.
- Forty-eight pressure sensors were installed, half in the Atlantic locks and half in the Pacific locks.
- Eight flowmeters were installed, again half for the Atlantic side and half for the Pacific.
- Three acoustic Doppler current profilers were installed, one on the Atlantic side and two on the Pacific side, to measure the surface water velocity in the approach channels on the centerline of the locks. Active construction precluded deployment of a second profiler on the Atlantic side.
- A series of permanent water-level sensors also were installed to monitor the water levels in the lock chambers and the water-saving basins. The data acquisition system monitors water levels at 27 separate locations on the Atlantic side and 27 on the Pacific.
- Valve position sensors were installed on each of the valves that control the flow of water into and out of the lock chambers. The system monitored 52 valve positions throughout the testing period. Furthermore, 16 culvert valve positions and 36 conduit valves also were monitored.

All of this equipment was able to interface with a custom-designed central data acquisition system to log data for testing in order to confirm that the design requirements were met.

The limited but systematic testing performed on the lock complexes enabled the performance team to determine compliance with the requirements for the test conditions. Moreover, the team also considered the results of tests from a 1:30 scale physical model of the new locks conducted in Lyon, France. Analyzing the physical model testing data together with the field data from strategic testing provided the ACP with the information required to understand how the system performs in relation to the requirements. Field-testing every operating condition that was tested in the physical model was not feasible.

Whenever possible, the performance team completed the testing at the actual lock under operating conditions in which the laboratory testing had shown the system performance to be closest to the limits set by the ACP. For cases in which it was not possible to test the actual lock for the most adverse performance conditions, the available testing was used to determine how the lock's performance differed from the physical model.

The field-testing was critical in demonstrating to the project owner how system performance compares with the design specifications. The independent testing was also used to determine if the design/build team had satisfied its contractual obligations for design and construction of the system. Independent performance testing is an important aspect of large design/build projects in that it gives the project owner and the bidders assurance that the design/build team will satisfy the project specifications.

Norman F. Perkins, P.E., M.ASCE, is the chief operating officer, Daniel Gessler, Ph.D., P.E., D.WRE, M.ASCE, a vice president, and Philip S. Stacy the director of calibration services at Alden Research Laboratory, Inc., of Holden, Massachusetts.

The walls of the new locks also feature an external drainage system designed to reduce the hydrostatic pressure on the outsides of those structures.

pairs. Each gate is 57.6 m wide. The gates range in size from 22.28 m tall and 8 m thick for the ones farthest inland on each side of the canal to 33.04 m tall and 10 m thick for the gates closest to the Pacific entrance to accommodate the aforementioned tidal variations there. Although the gates each weigh between 2,313 and 4,242 metric tons, they feature buoyancy chambers that enable them to float and thereby roll on rails at just 15 percent of their actual weight.

One problem with the miter gates on the original locks is that they require considerable maintenance, notes Stantec's Pansic. "And whether that involves damage from a vessel impact or just that they need to be recoated for corrosion protection, it's a fairly elaborate and time-consuming process to remove them and take them to a dry dock where you can work on them," he explains. Moreover, that canal lane must be shut down, sometimes for a considerable amount of time, until a replacement gate is installed.

But since the expansion project added just one lane, the locks must remain in operation even if a gate requires maintenance or repair, Pansic says. The solution involved the use of rolling gates in pairs, each gate having a recessed space into which it can be retracted and then sealed off with a bulkhead. The recessed area can then be dewatered and the gate repaired or maintained in the dry while its duplicate continues to open and close the chamber for ship transits, Pansic explains.

The new rolling gates range in height from 22.28 m to 33.04 m, depending on location.

"With the single lane of locks there was a huge premium on high reliability and high availability of all of the systems," Pansic notes. "So the rolling gates proved to be the most reliable and the most available lock gate system for that application."

The walls of the new locks also feature an external drainage system designed to reduce the hydrostatic pressure on the outsides of those structures, an idea that Stantec initially developed for a U.S. Army Corps of Engineers project involving locks in Kentucky. The ACP agreed to use a similar system on the new set of locks provided that it could be easily maintained, Newbery notes. So the drains were included behind the walls, along with shafts to provide maintenance access, he says. The drains themselves are "about six feet high and two feet wide, so you can literally walk inside and clean them out if you need to," he explains.

On the Pacific side, the construction of the Borinquen Dams involved the use of both a primary and a secondary grouting to seal the rock beneath the structure. The dams themselves, which are as much as 100 ft high, are zoned embankments that feature a clay core protected by filters and have sloping rock walls armored with riprap.

At the approaches to the lock complexes at either end of the canal, reinforced-concrete guide walls help align the neo-Panamax vessels as they enter the chambers. An array of fenders designed to cushion ship impacts helps ships safely maneuver into the chambers with the aid of tugboats.

Both the Atlantic and the Pacific lock complexes house the supplementary systems needed for operation and maintenance, including enclosed galleries that provide dry access beneath the chambers. High-mast lighting systems facilitate around-the-clock transits, and duplicate loop power systems connect all critical operating equipment to two power supplies as well as to a standby generator. Each lock complex has 60 support buildings, including machinery buildings that house the electrical and mechanical equipment for lock gate and valve operations, as well as other operations and maintenance structures. Other site infrastructure includes access roads, storm drainage, security fencing, and surveillance and access-control systems.

To mitigate the expansion project's effect on the Panamanian environment, ecological compensation and reforestation efforts were conducted throughout the country, resulting in the rescue and relocation of more than 6,000 mammals, birds, reptiles, and amphibians, as well as the establishment of nearly 1,000 hectares of new vegetated spaces at parks, forests, and other locations. In essence, each hectare affected by the expansion program was offset by two new "green" hectares.

Archaeological and paleontological items discovered during the excavations and other work for the expansion project were recovered and preserved with the assistance of the Smithsonian Tropical Research Institute, which is based in Panama. More than 5,300 rock and sediment samples and more than 3,400 fossils were collected and cataloged.

Functionally completed in early June last year, the new locks underwent a series of successful trials prior to the inauguration of the expanded facilities, which took place on June 26. "More than 100 years ago, the Panama Canal connected two oceans," noted Jorge L. Quijano, the ACP's chief executive officer. "Today, we connect the present and the future."

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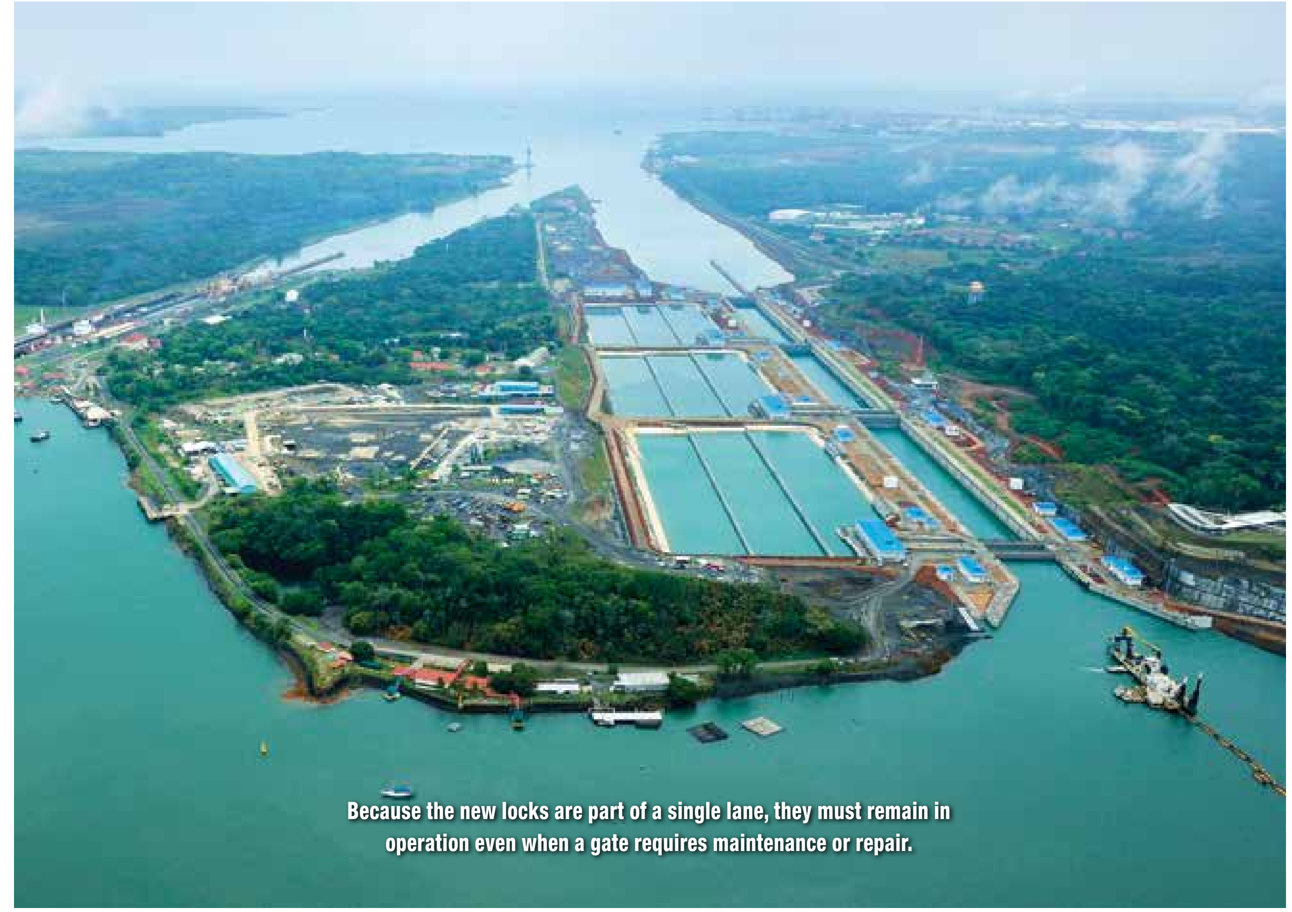

Because the new locks are part of a single lane, they must remain in operation even when a gate requires maintenance or repair.

Since then, the expanded canal has experienced several consecutive months of record daily tonnages for ships availing themselves of the new locks, and in March 2017 the 1,000th neo-Panamax ship passed through the waterway. The expansion also opened the canal to new market segments. In July 2016, for example, the first tanker transporting liquefied natural gas ever to enter the canal transited the new locks, and the number of such tankers using the locks has been exceeding the ACP's expectations, averaging more than five per week, not the one per week that the ACP expected.

And it's not just Panama that has benefited from the expanded canal. According to an ACP press release that announced that 1,000th neo-Panamax vessel, "ports around the world, and in particular along the U.S. East Coast, have already expanded or are in the process of deepening and widening their channels to accommodate the influx of neo-Panamax vessel traffic due to the expansion." Moreover, many of these ports have also experienced record tonnage months, the ACP release noted.

Pansic says he's seen improvements and upgrades to maritime infrastructure projects around the world, from U.S. inland waterways to Europe, Asia, and the Persian Gulf. There's been "a huge knock-on effect in terms of driving investment in other facilities, larger maritime port facilities…to better take advantage of what the expanded canal can offer," Pansic explains. These investments, he adds, "wouldn't have happened if the canal hadn't been expanded." **CE**

Reid

Robert L. Reid is the senior editor and features manager of Civil Engineering.

PROJECT CREDITS Owner: Autoridad del Canal de Panamá (Panama Canal Authority) **Design/build consortium:** Grupo Unidos por el Canal, SA, consisting of Sacyr Vallehermoso, S.A., Madrid, Spain; Salini Impregilo S.p.A., Milan, Italy; Jan De Nul NV, Aalst, Belgium; and Constructora Urbana, S.A., Panama City **Third set of locks joint venture design team:** Consultores Internacionales del Canal de Panamá, LLC, consisting of numerous offices of MWH Global, a Stantec Company; Tetra Tech, Inc., Pasadena, California; and Iv-Groep b.v., Papendrecht, the Netherlands **Pacific entrance dredging:** Dredging International NV, part of DEME, Zwijndrecht, Belgium **Atlantic entrance dredging:** Jan De Nul NV, Aalst, Belgium **Gate fabricator:** Cimolai Technology SpA, Carmignano di Brenta, Italy **Pacific access channel consortium:** FCC, Madrid, Spain; ICA, Mexico City; and Constructora Meco SA, San José, Costa Rica, office **Lock complexes testing:** Alden Research Laboratory, Inc., Holden, Massachusetts; Cameron, part of Schlumberger, Houston office; Flowmeter Service, Northampton, Massachusetts; and Rennasonic, Inc., East Falmouth, Massachusetts, and Naples, Florida