Difficult ground conditions at the Panama Canal

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Abstract: Construction of the Panama Canal ranks high among the world's greatest feats of civil engineering. It included the world's largest earth dam (at the time) and concrete structures that are among the largest anywhere. The site is also remarkable for the dreadful geology that generated massive landslides during excavation of the Culebra Cut through the high ground.

Following their construction of the Suez Canal, an ambitious French team, led again by Ferdinand de Lesseps, set out for Panama with a plan that was doomed to failure. De Lesseps was a diplomat and developer, not an engineer, and was arrogant and all-powerful after his success at Suez. His dogmatic plan for a sea-level canal could never have been completed, as they could not achieve the necessary scale of rock excavation, starting more than 100 metres above sea level at the col through the highlands. Then their plan to canalise the Chagres River across the Atlantic-side lowlands was foiled by frequent floods on a scale never conceived by Parisians who had no experience of tropical weather. Worst of all, they did not understand the role of mosquitoes in spreading the malaria and yellow fever that killed more than 22,000 of their workmen. The average length of a working session on the canal for an engineer or manager sent out from Paris was just six months, not before they were sent home, but before they died of fever. The French withdrew from Panama in 1889.

Construction of the Canal

There followed some dubious political manoeuvers whereby the province of Panama seceded from the corrupt nation of Colombia, became independent, and immediately granted the Canal Zone to the United States. With political problems overcome, the Americans started work at Panama in 1904. It soon became a military project, in the hands of the US Army Corps of Engineers, and they actually had a navigable canal open within ten years (Fig. 1). This remarkable feat was achieved by a combination of limitless budget, massive effort and sheer brute force. At peak times there were 50,000 men working on the canal; most were from the West Indies, and included nearly half of all men of working age on the island of Barbados. Through all this, there were two key factors that ensured the canal's success.

First of these was disease control, made possible by new understanding of the role of mosquitoes. As Chief Sanitary Officer on the Canal project, William Gorgas attacked the insects' breeding grounds in stagnant water, by applying mixtures of carbolic, oil and caustic soda. Yellow fever was spread by the *Aedes* mosquitoes; these bred close to houses (which contained their food supply of human blood), so were easily traced and killed, and the dreaded yellow fever was thereby wiped out in the Canal Zone. The *Anopheles* mosquitoes that spread malaria are more widely distributed, wherever there is stagnant water; their numbers could only be reduced by the spraying programme, with the result that malaria was greatly reduced but not eliminated.

Second was the invention of the railway-mounted steam shovel and the manufacture of new larger models by the Bucyrus Company of Ohio. More than a hundred of these machines became critical in overcoming the horrendous geological conditions that were soon encountered in the great Culebra Cut where the canal traversed the highest ground between the oceans.

Due to the twisting geography of the Central American Isthmus, the Panama Canal has ships sailing westwards on their way from the Pacific to the Atlantic (Fig. 2). Some 82 kilometres in length, the canal has two distinct halves. Its southeastern half, on the Pacific side, between Panama City and Gamboa is cut through the isthmian highland chain, whereas the northwestern half out to Colon on the Caribbean coast is across the lowlands of the lower Chagres River.

Even when they started work, the Americans had no clear plan. Their first target was a sea-level canal, which was still favoured by many of the congressional committees that ran the project from Washington, and was distressingly slow to lose its support. Seen in retrospect, it is widely considered that a sea-level canal could have proved impossible to complete, and it would certainly have cost far too much and taken

***Figure 1**. Panama Canal in the excavated section between the Culebra Cut and Gamboa.*

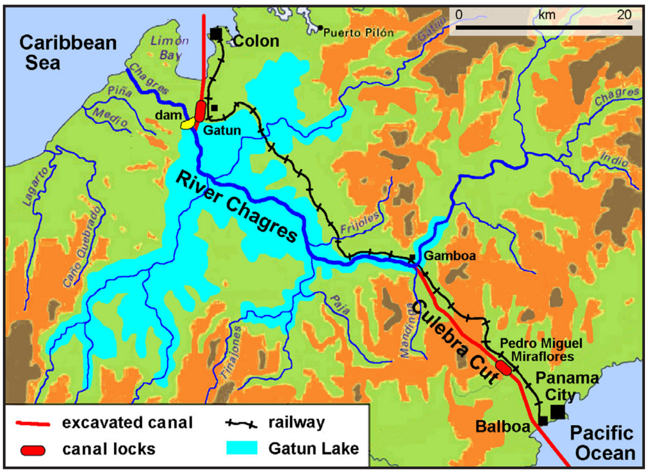

Figure 2. The area around the Panama Canal showing the rivers as they were before impounding of Gatun Lake in 1912, behind the dam on the River Chagres; the railway had been in place since 1855; the Madden Dam and Lake Alajuela are not shown as they were added in 1935.

Figure 3. Ships passing each other in the Chagres valley west of Gamboa, where it was inundated by the waters of Gatun Lake.

too long to build. A canal across Nicaragua was still favoured by too many politicians. It was more than a year after work had started at Panama that the project finally evolved into the structure of a lock canal.

Gatun Lake

It had long been known that a major difficulty in any Panama scheme would be dredging and canalising the flood-prone Chagres River, where levels could rise ten metres in a single day after a fairly routine tropical rainstorm. The key to successful completion of the lowland section of the canal was construction of a dam on the Chagres, to impound Lake Gatun (Fig. 2). At a stroke, and after removal of a few ribs of rock, this created a navigable waterway upstream to Gamboa (Fig. 3). Furthermore, this huge impounded lake could absorb the peaks of the floods coming down from the upper Chagres, would maintain a reliable supply of water to feed through the locks when traversed by ships, and could generate hydro-electricity at a power station beside the dam's spillway. There would then be a flight of three locks beside the dam at Gatun, matching three locks near the Pacific end of the canal

This was a remarkably simple and almost obvious plan. It had first been suggested in 1879 by Godin de Lépinay, a French highways engineer, but was ignored when submitted to the autocratic de Lesseps. The concept of a dam on the Chagres was then suggested anew by a Brooklyn Waterworks engineer, Charles Ward, after he visited the French site in 1880, but the Americans started on the canal project in 1904 with minimal solid plans and no thoughts on any dam. John Stevens became the second in post as Chief Engineer, and it was he who picked up on Ward's concept and turned it into reality after seeing the Chagres River in full flood.

When it was constructed, the Gatun Dam was the largest earth structure in the world, with the largest concrete spillway, impounding what was then the world's largest artificial lake. The dam is only 32 metres high but has a crest length of 2500 metres, with a concrete spillway structure 245 metres wide near its centre. Geology influenced the dam design after trial borings revealed two buried channels of the Chagres, reaching depths of 60 metres (Fig. 4). The concrete spillway was therefore founded on a sandstone ridge between the two channels. Fortunately, the sediments filling both channels were stiff clays that were both impermeable and able to bear the modest loading imposed by the earth dam. As with many earth dams, there were minor slumps of the structure while it was being built up; the largest of these was due to inadvertently covering the weak organic fill that had accumulated in the abandoned French canal.

Clay for the dam's watertight core was sourced from dredging operations in Limon Bay that deepened a channel out to the open sea. There was no shortage of rock fill for the bulk of the dam's structure, with broken stone coning from both the Culebra Cut and the excavations for the Gatun locks.

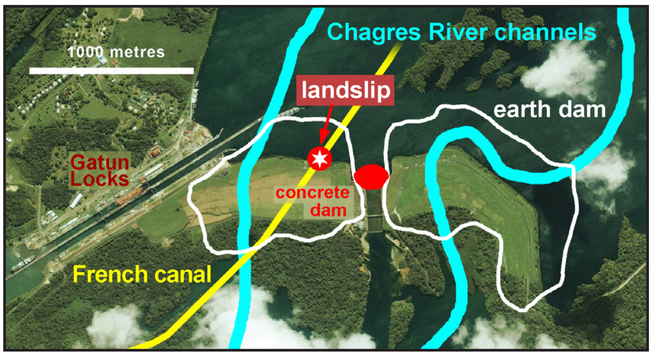

Figure 4. Gatun Dam, with the pale green grass cover on the downstream slope of the earth barrier that lies across the old channels and sediment-filled valleys of the River Chagres (satellite image from Google Earth; white patches are clouds).

Panamax locks

The Panama Canal locks are still among the world's largest concrete structures. Each lock is paired, so that there are six at Gatun, four at Miraflores, and two at Pedro Miguel (a short way above Miraflores). Each is the same size, designed to take the largest ship in the US Navy at the time. The dimensions subsequently influenced ship building around the world, when most large new ships were built to 'Panamax' dimensions, as determined by the width, length and depth of the locks. Most critical is the width, whereby ships with a Panamax beam of 32.3 metres pass through locks that are just 33.5 metres wide. The minimal clearance means that ships are guided through the locks by 'mules'. Named after the real mules that carried the first trade goods across the Panama isthmus, these are electric-powered, rack-and-pinion locomotives running on tracks adjacent to each lock (Fig. 5). Ships transit the locks under their own power, but are accurately positioned by cables to the mules that keep alongside; there can be four or eight mules attached to each ship, with one or a pair at each corner, and the whole operation is under central computerised control.

Each lock raises or lowers ships by 8.6 metres, to achieve the canal's summit level nearly 26 metres above sea level. The lower Miraflore Lock can also cope with the Pacific's tidal range of some 4 metres, whereas the Caribbean has a tide of less than a metre bearing on the lowest of the Gatun locks. The story and superlatives of the construction and operation of Panama's locks could run and run, but the most memorable feature of the canal's geology lies in the massive Culebra Cut that allows ships to pass through a considerable range of hills.

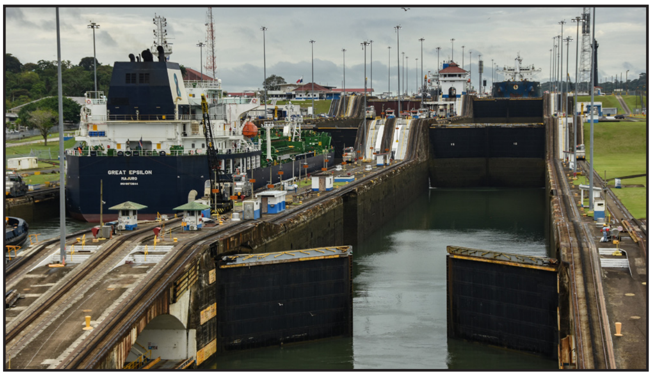

Figure 5. *Ships passing in both directions through the Gatun Locks.*

Landslides in the Culebra Cut

Between a crest altitude of 107 metres on the water-shed divide and a canal floor level of 12 metres, excavation of the Culebra Cut (also known in the past as the Gaillard Cut) was always going to be a massive undertaking (Fig. 6). For nearly five kilometres of its length, it required excavation down to depths of more than 50 metres below original ground level; maximum depths were more than 100 metres. The original plans called for steep rock walls with a rim width of

Figure 6. *Excavations in the Culebra Cut during 1913, looking north from Contractors' Hill, with rock terraces in Gold Hill on the right, the toe of the Cucaracha Slide lower right, and the lower slopes of the West and East Culebra Slides in the distance (photo: U.S. National Archives).*

little over 200 metres; but the excavated faces flared out with repeated slope failures and landslides, until parts of the Cut reached widths of 1500 metres. Total excavation eventually exceeded 150 million tonnes. It was a mammoth project, which was managed with military rigour and with massive quantities of heavy machinery. Some 120 kilometres of railway tracks were moved about on multiple benches within the Cut, and up to 500 trains each day were either outbound loaded with excavated debris or inbound empty. Most of the rock debris went into landfill that extended the Pacific shoreline and on which now stands the town of Balboa, though some went into the dam at Gatun. With its machine operations and its great landslides, the Culebra Cut became a popular tourist attraction, pulling in 20,000 visitors in 1912 alone.

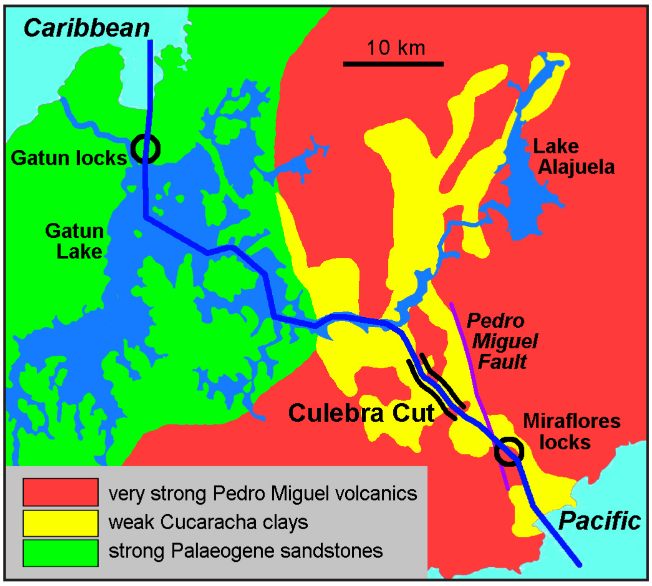

Figure 7. *Main geological units in the Canal Zone, simplified in terms of their rock strength; the line of the canal is shown in dark blue, including its excavated section through the high ground on the Pacific side, its alignment across Gatun Lake, and the dredged channels out through the coastal shallows.*

Three Neogene rock formations dominate the geology of the Culebra Cut. As might be expected, the highest ground was largely formed of strong rock (Fig. 7). Much of the excavation was therefore in the Pedro Miguel Formation, which consisted of andesites, tuffs and agglomerates, all of which required drilling and blasting. The two high points, Gold Hill and Zion Hill, are both capped by equally strong basalts. Beneath the volcanics, the Cucaracha Formation is dominated by its famously weak clays, and beneath them, with only little at outcrop, lies the Culebra Formation of reasonably strong sandstones. Numerous faults, lying both across and along the canal axis, create major changes every few hundred metres along the walls. Different again are the Paleogene sandstones that underlie the lowlands out towards Gatun and the Caribbean.

The walls in the Culebra Cut failed in a spectacular variety of landslide (Fig. 8). Rock falls were numerous and mostly small. Slab failures were larger and mainly developed in stronger volcanic rocks overlying weak clays (Fig. 9). Largest of all were rotational and translational landslides that developed in and above the easily sheared clays. Within the Culebra Cut, critical stages were reached whenever and wherever excavations down through the volcanic rocks and into the underlying Cucaracha clays. This allowed extensive shear surfaces to develop within the clays, and the three largest landslides all crept into activity while engineering works were still in progress (Fig. 10). The faulted and variable sequence of volcanic rocks already had a history of small slope failures, but their generally high strength became irrelevant when they were undermined by failure of the clays beneath. The two Culebra Slides were deep-seated. It appears that the main shear planes at depth developed at least partly along gently dipping bedding planes or within the weakest clays of the Cucaracha Formation. However, uplift at the slide toes was observed when ground rose by as much as ten metres above slip surfaces that curved upwards to the surface. One engineer reported how the floor of the excavations lifted by two metres within about five minutes where it lay on the toe of a rotational slide.

***Figure 8**. One of the many landslides into the Culebra Cut during the work of excavation (photo: U.S. National Archives)*

***Figure 9**. Slab failure into the shallow part of the canal trench between the Culebra Cut and Gamboa. A mass of strong volcanic rock has failed in front of a low-angle oblique fault, and has pushed underlying clay up into the floor of the excavations (photo: U.S. National Archives).*

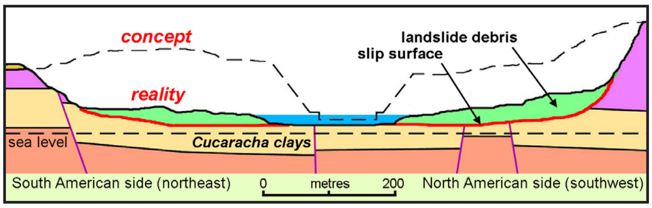

***Figure 10**. Profile across the Culebra Cut where the East and West Culebra Slides had moved into the excavations; the broken line shows the original ground profile together with the profile of the Canal trench as planned before the landslides were recognised.*

Cucaracha clay

Subsequent analyses of clay from the Cucaracha Formation have shown it to be remarkably weak (Fig. 11). It is composed largely of smectite, the weakest of all clay minerals, which is created by weathering of volcanic rocks in hot and wet tropical conditions. Parts of the Cucaracha Formation are recognisable for their pyroclastic content, and it is likely that much of the clay has an ash component, with the rest derived from weathering of the region's older volcanic rocks. With this high smectite content, the internal friction angle of Cucaracha clay has been measured at values as low as 4°, with obvious implications for its stability in slopes.

A significant weakness of the Cucaracha clay is its major decline in strength due to restructuring when it is deformed. Shear stress imposed by differential loading within the geometry of a slope profile may overcome the strength of the rock at a value known as its peak strength. Then, the induced strain and deformation within the rock causes re-alignment of its minerals, so that shear planes can develop more easily. The strength of the rock thereby declines to a value known as its residual strength. Clay is particularly susceptible to this restructuring, and the residual strength of Cucaracha clay is only about 25% of its peak strength.

Figure 11. Cucaracha clay exposed at the edge of the Canal

Consequently, landslides that started within the Culebra Cut continued to move due to the reduced strength in their basal layers.

The landslides in the Culebra Cut were too large to be stabilised, so the engineers took the only available option of letting the slides run and removing the debris as it arrived. This was where the massive capability of the American steam shovels proved to be invaluable. Eventually, the canal was allowed to fill with water, by removing the dyke at Gamboa. Floating dredgers could then be brought in, with their greater manoeuvrability giving them more capacity for removing the slide debris as it continued to creep into the excavations.

Continued activity of the landslides

Landslides within the Culebra Cut were a major feature of the excavation phase and also for a long time afterwards. The first official transit of the canal was made by the SS Ancon, with its cargo of dignitaries, on August 15, 1914, though small company ships and tugs had been passing through for some weeks previously. Opening of the canal was however not the end of the landslides, which caused a total of 26 temporary closures up until 1986. Initially, and during the war years, transits were restricted to military shipping. Then in July 1920 the canal was opened to all commercial traffic, but still the landslides continued. Small landslides had been a recurring feature of the massive Canal excavations; wet-season failures of clay slopes and small rockfalls became almost routine events.

The Cucaracha Slide was the first to develop on a large scale when mass wasting extended in front of a long head scar late in 1907 (Fig. 12). This slide was largely formed of the Cucaracha clays, and it reached no great thickness over a relatively shallow slip surface. Continuing heavy rainfall saturated the clays, so that the whole slide mass crept downslope at a steady four metres per day. It was described at the time as a tropical glacier made of mud instead of ice.

Most of the small hill-top town of Culebra was carried away by the West Culebra Slide when its head scarp retreated and enlarged the slide in a series of events (Fig. 13), while the East Culebra Slide developed in the opposite bank. This pair of slides lies in the deepest part of the Culebra Cut, where most of its depth had been laboriously excavated down through the strong volcanic rocks. Both were classic deep-seated slides with larger masses of the hard volcanic rocks moving above slip surfaces within the underlying clay (Fig. 10). In the long term these displaced huge thicknesses of rock and generated more debris to be removed from the advancing toes than did the shallow Cucaracha Slide.

With continuing movement, and while slide debris was still being removed from the toes, material was removed from the upper parts of the landslides, thereby reducing their driving forces. The end effect was huge expanses of gently sloping ground extending to as much as 700 metres away from the canal banks. Widening of

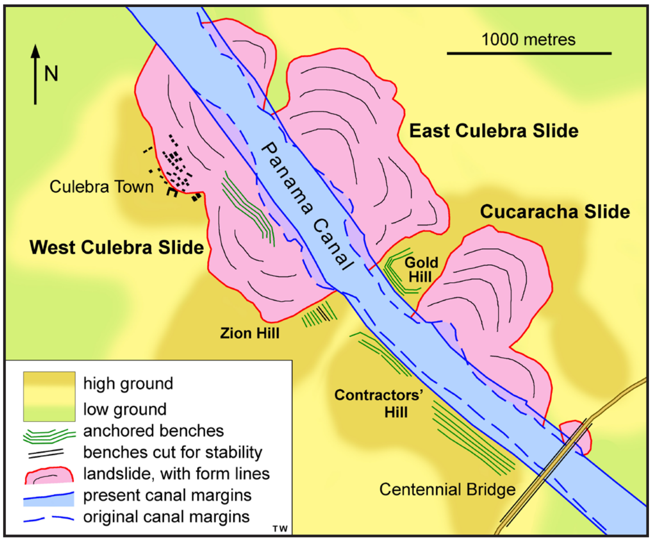

***Figure 12**. The major landslides and rock hills along the deepest part of the Culebra Cut; the Centennial Bridge was a much later addition.*

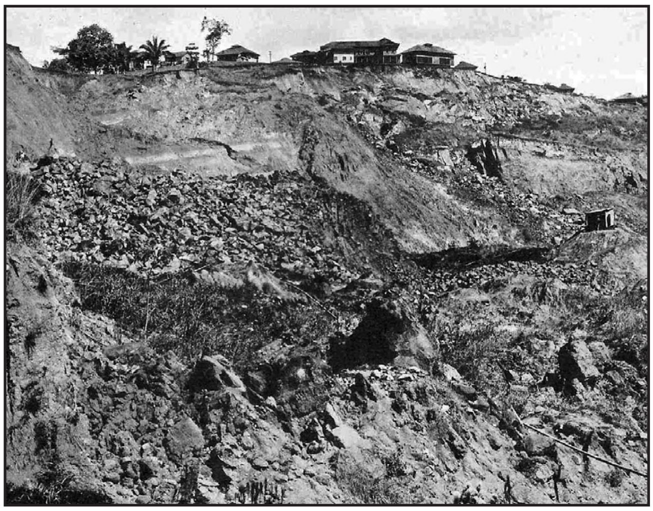

***Figure 13**. The West Culebra Slide expanding headwards and progressively undermining the houses of Culebra village (photo: U.S. National Archives).*

***Figure 14**. The distinctive terraced rock face on Gold Hill, with the broken ground of the Cucaracha Slide on the right, still creeping into the Canal within the Culebra Cut.*

the canal during the 1950s also included re-profiling of the lower slopes. Since then, ground movements have continued, but at reducing rates. Floating suction dredgers have proven to be the best way of removing slide debris that has slumped into the canal; they can also excavate any parts of the canal floor that have lifted at the toes of rotational slip surfaces.

Each fault block along the canal has its own geological structure, which may or may not create problems of instability, and significant throws on the cross faults meant that the top of the Cucaracha Formation lies at different levels in each block. Some hills therefore survive with cut faces in strong rock, but these are not necessarily stable. The most conspicuous is Gold Hill (which contains no gold), with its high, benched face forming a well-known landmark along the canal (Fig. 14). It is stable, and the few rock-bolts visible on its faces represent only minor, localised, safety measures. In contrast, the rock spur of Zion Hill, forming the southern flank of the West Culebra Slide, recently started to slide over the underlying clay. Its face was therefore benched, and the whole buttress of volcanic rock is now held intact by an array of long rock-anchors (Fig. 15).

***Figure 15**. The cut face of Zion Hill in the Culebra Cut; the terraced face in the Pedro Miguel volcanic rocks is constrained by 250 rock anchors to prevent it from sliding out over the underlying Cucaracha Clay that has been cut back to a gentle profile.*

Improving the canal

A protracted phase of widening during the 1950s could not make major changes to the big rock faces in the Culebra Cut, where large ships are still restricted to alternating periods of one-way traffic (though ships can pass each other on Gatun Lake and in the lock approaches). Another new feature was the Madden Dam, completed on the upper Chagres River in 1935. This impounded Lake Alajuela, which allows improved control of flood peaks, but is more important in holding water to replenish Gatun Lake during the four months of annual dry season when more water is released through the locks than is provided by rainfall.

More significant than widening the canal has been the building of wider locks. A major event in the canal's history occurred at the end of 1999 when the USA handed the canal and its infrastructure over to the state of Panama. New large container ships were already dominating world trade, and within a few years about a third of them were too large to transit the Panama Canal, or more specifically to pass through the locks. So in 2006 Panama held a national referendum, in which 76% of the voters supported taking out a giant slice of the state's tax budget in order to spend five billion dollars on building new larger locks that would ensure the future of the canal and its earnings.

Starting in 2007, construction of the new, larger locks became another giant piece of civil engineering. They used more than seven million tonnes of concrete, but all were completed for the first transits of the larger ships in June 2016. "Neopanamax" dimensions, as determined by the new locks, allow ships to carry 6500 standard 12-metre-long containers, as opposed to 2500 on the older Panamax ships. There are just six new locks, in two triple flights without parallel duplication. They lie beside the original locks, which are still used to transit most of the smaller ships (Fig. 16).

Besides the size of the new locks, some features differ from those of the old. Instead of traditional hinged gates, they have massive sliding gates that were copied from designs on Belgian locks. Each lock is also

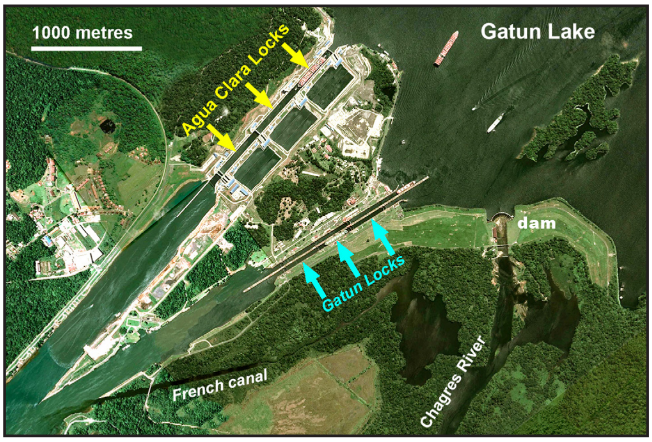

***Figure 16**. Features of the Canal at Gatun, including the new Agua Clara Locks, the original Gatun Locks, the remains of the French canal, the Gatun Dam, and part of Gatun Lake. (satellite image from Google Earth).*

accompanied by a multi-level set of water-conservation basins, which allow 60% of the water to be retained and re-used instead of all being lost whenever a ship goes either up or down through the locks (Fig. 16). These basins are a critical innovation, as the amount of water in the Chagres catchment imposes a limit on total lock use, which is now far from being reached due to the new measures of water conservation. The new locks also lack the guiding electric mules, because modern ships are so much more manoeuvrable under their own power; however some ships have hit the lock walls, and the mules could be sorely missed.

The new Agua Clara Locks are at the Atlantic end of the canal, adjacent to the old Gatun Locks. Away from the mountain axis, their ground conditions were relatively simple. Paleogene sandstones and mudstones that are strong and massively bedded allowed steep faces to be cut for the lock excavations, which remained stable prior to backfilling around the concrete structures.

At the Pacific end of the canal, the triple Cocoli Locks represent the upgrade of both the Miraflores and the Pedro Miguel Locks. They lie alongside the Miraflores Locks, so the high-level canal above them passes beside the Miraflores Lake that lies 9 metres below and extends as far as the Pedro Miguel Locks (Fig. 17). The new canal is therefore retained behind the Borinquen dams that total 2300 metres in length long where they overlook the Miraflores Lake (Fig. 18). Effectively forming the canal banks, these dams have a conventional design with a clay core of local surficial residual soils inside a rock-fill that is largely of basalt from the lock excavations. The dams stand on adequately strong sedimentary rocks, but these are broken by the potentially active Pedro Miguel Fault. Field studies and modelling indicated that this could offset by about a metre within the canal's lifetime, but such a displacement can be tolerated within the flexible dam structure. Any accompanying earthquake, up to Magnitude 7, would threaten neither the dams nor the concrete lock structures.

***Figure 17**. A ship and one of its guiding mules in the Miraflores Locks; in the background, a container ship on its way to the Cocoli Locks is in the high-level canal retained behind the Borinquen earth barrier.*

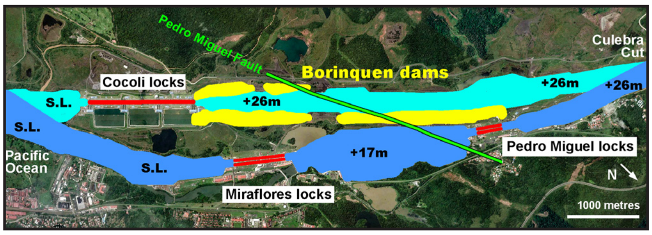

***Figure 18**. Features of the locks at the Pacific end of the Canal, with the alignment of the Pedro Miguel Fault that underlies the Borinquen dams confining the high-level canal as far as the new Cocoli Locks; the gaps in the yellow of the dams are where the earth barriers abut onto existing bedrock hills (satellite image from Google Earth).*

The expanded canal has already proved to be a great success for the Panama nation, and the new lock dimensions assure its future. There are a few container ships that are too large to transit the new locks (whereas they can pass through the Suez Canal), but large numbers of new ships are being built to Neopanamax dimensions. Perhaps the greatest threat to the future canal traffic is climate change, which could open the Northwest Passage between Canada's Arctic islands and provide a shorter route from eastern Asia to Europe, but this would only be for a part of each year.

In 2012, a Chinese company started ground surveys and initial planning for building a canal through Nicaragua, thereby resurrecting the early American scheme, though with larger locks. However, this appears to have been little more than a political gesture, which quietly disappeared soon after Panama's new larger locks were opened in 2016. A Nicaraguan canal would be longer in total than Panama, but nearly half its length would be across the natural Lake Nicaragua, which lies at 32 metres above sea level. Perhaps of some significance is the fact that the lake's shipping route would pass very close to the island volcano of Concepcion, which has frequent eruptions, albeit of modest scale. With regard to any inter-ocean canal, that volcano could constitute an unusual geohazard to match that of the landslides in the Culebra Cut.

Further reading

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