Feature

Civil engineering meets geology: at the Panama Canal

The Panama Canal ranks high among the world's greatest feats of civil engineering. The sheer scales of its ground excavations, its concrete structures and its economic significance are truly spectacular. It is also remarkable for the geology of the massive landslides that developed within its Culebra Cut.

Tony Waltham
Nottingham, UK
tony@geophotos.co.uk

A survey ordered by the King of Spain in 1534 was the first of many fanciful plans for a shipping route to link the Atlantic and Pacific oceans. However, it was the French who first began excavation of a canal in 1882. Their chosen route between Colon and Panama City followed close to that of the Panama Railroad. This had been operating successfully since 1855, because it had the singular advantage of being able to traverse hills.

Buoyed by enthusiasm after their completion of the Suez Canal, the French team led by Ferdinand de Lesseps set forth 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 was supported by diplomats who out-voted engineers on the remote organizing committee in Paris. Furthermore, nearly all of the French team were horribly ignorant of conditions in the tropical rain forests of Panama and therefore created their own train of failures. They could not handle the necessary scale of rock excavation that had to start more than 100 m above sea level at the lowest point on the highlands' watershed divide. Then their plan to canalize the Chagres River across the Atlantic-side lowlands was foiled by frequent floods that would raise its level by 10 m within a single day. And 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.

The succeeding years were dominated by politics. At that time, the canal site was within the Panama province of Colombia, which was a seriously unstable nation. So the Americans were assessing the scope for a canal through Nicaragua. Meanwhile, with new funds and a new plan, the French re-started work at Panama in 1895, before retreating again in 1898. Attempts to sell the embryo canal to the USA were thwarted by the Colombian government. Matters changed in 1903, when, after a revolution lasting just 10 days, Panama achieved independence from Colombia. American support for this had been significant, and no more than five days after the birth of the new nation, the Panama Canal Zone was handed over to the USA, with agreement to construct and manage a canal.

Construction of the canal

With political hurdles cleared, and their army and navy commanders pressing home the strategic importance of a canal, the Americans started work at Panama in 1904. It was a military project, in the

Fig. 1. Ships on the middle section of the Panama Canal, between the Culebra Cut and Gatun Lake.

hands of the US Army Corps of Engineers, and they actually had a navigable canal open within ten years (Fig. 1). They achieved this remarkable feat and timing by a combination of commendable planning, a limitless budget, massive effort and sheer brute force. Within all this, there were two key factors that ensured the canal's success.

First of these was disease control. In 1881, a Cuban scientist, Carlos Finlay, had suggested the role of mosquitoes. The British doctor Ronald Ross, working in India and subsequently a Nobel laureate, confirmed the role of mosquitoes in transmitting malaria, and Walter Reed of the US army proved their transmission of yellow fever. Thus armed, William Gorgas, Chief Sanitary Officer on the Canal project, controlled the insects by attacking their breeding grounds in stagnant water with sprayed mixtures of carbolic, oil and caustic soda. It has to be seen as a success that only 5600 workman died during the American phase in Panama's forests during a time prior to the development of insecticides.

Second was invention of the steam shovel and their manufacture on a grand scale. This opened the way for truly massive earthworks and became critical in overcoming the horrendous geological conditions that were subsequently encountered in the great Culebra Cut where the canal traversed the highest ground between the oceans (Fig. 2).

Due to the twisted geography of the Central American Isthmus, the Panama Canal has ships sailing westwards on their way from the Pacific to the Atlantic (Fig. 3). Some 82 km in length, the canal has two distinct halves. Its southeastern half, on the Pacific side, between Panama City and Gamboa is cut through Panama's highland chain, whereas the northwestern half out to Colon on the Caribbean coast is across the lowlands of the lower Chagres River.

Fig. 2. The Culebra Cut during the American excavations, looking towards the northwest. The steep rock face cut into Gold Hill is on the right, and the lower slopes beyond would subsequently further degrade into the West and East Culebra Slides. (Historical photographs of the American excavations are from the archives of the National Academy of Sciences in Washington.)

Gatun Lake

The original American plan for a locked canal had three locks at the Pacific end to take the canal up to an altitude of 26 m, which was considered to be an optimum for an elevated route through the highlands. On the Atlantic side of the divide, there would then be two locks near Gamboa, taking the canal down to the River Chagres, and a third lock at Gatun taking the canal away from the estuary and out and down to Limon Bay and Colon. This would require some extensive works to canalize the channel of the Chagres and also on-going maintenance to accommodate the seasonal flooding of the river.

But such was not to be, as both the canalization and the maintenance could be largely eliminated by the creation of a lake. Construction of a dam on the Chagres, to impound Lake Gatun, was the key to successful completion of the lowland section of the canal (Fig. 3). The locks at Gamboa would no longer be needed as the lake waters would back up into the Culebra Cut. Instead there would be a flight of three locks at Gatun. There were also enormous savings in avoiding the difficult dredging and canalizing of the flood-prone Chagres River. In addition, the huge impounded lake could absorb the peaks of the floods coming down from the upper Chagres and would maintain a reliable supply of water to feed through the locks when traversed by ships.

This was a remarkably simple and almost obvious plan. It had first been suggested in 1879 by Godin de

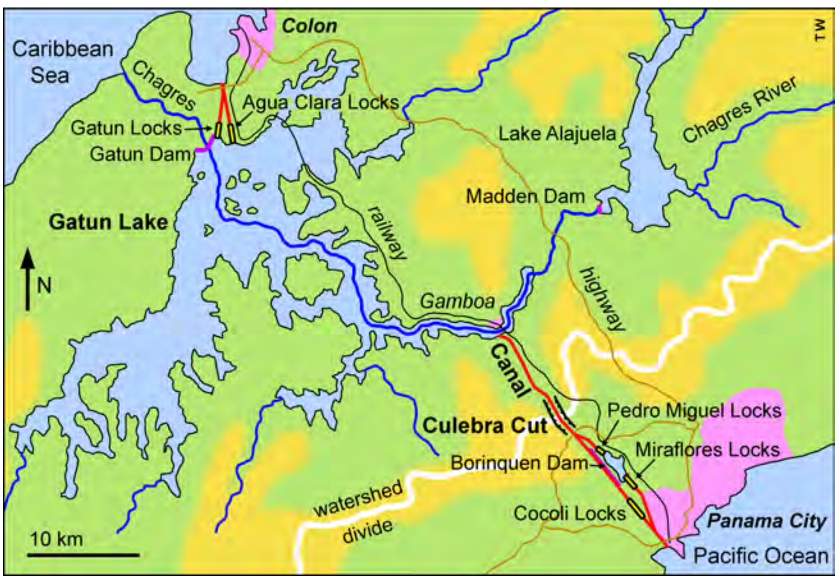

Fig. 3. Main features of the Panama Canal. The shipping route across Gatun Lake follows a slightly straightened course that lies almost above the drowned channel of the Chagres River. The railway is in its present alignment, after part of its original route was lost beneath Lake Gatun.

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 engineer, Charles Ward, after he visited the French during their initial stage of on-site planning 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, and it impounded what was then the world's largest artificial lake. The dam is only 32 m high but has a crest length of 2500 m, with a concrete spillway structure 245 m wide near its centre. Most of its earth and rock fill came from excavations for the adjacent Gatun Locks, with some material also brought from the Culebra Cut. Geology influenced the dam design after trial borings revealed two, deep, buried channels of the Chagres, both filled with sediment. The concrete structure was therefore founded on a sandstone ridge between the two channels, and only the wide earth shoulders of the dam bear on the channel fills. Gatun Lake has an incidental benefit in its largest island, that of Barro Colorado. Lying just south of the canal's shipping route, this was surrounded and isolated by the lake's rising water, hence preserving its fragment of pristine rain forest that has become an invaluable research site.

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, two at Pedro Miguel and four at Miraflores. Each is the same size, which was designed to take the largest ship in the US Navy at the time. The dimensions then influenced ship building around the world, when most large new ships were built to 'Panamax' dimensions, which are determined by the width, length and depth of the locks. Most critical is the width, whereby ships with a Panamax beam of 32.3 m pass through locks that are just 33.5 m 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. 4). 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 control.

Each lock raises or lowers ships by 8.6 m to achieve the canal's summit level nearly 26 m above sea level.

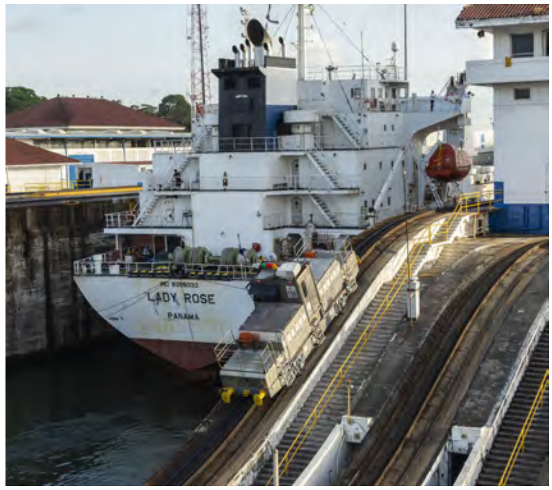

Fig. 4. One of the team of electric 'mules' guiding a ship through the Gatun Locks.

The lower Miraflore Lock can also cope with the Pacific's tidal range of some four 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 memorable feature of the canal's geology lies in the massive Culebra Cut that allows ships to pass through a very considerable range of hills.

Landslides in the Culebra Cut

Between a crest altitude of 107 m on the watershed divide and a canal floor level of 12 m, excavation of the Culebra Cut was always going to be a massive undertaking. Named after the small town of Culebra, which stood at the edge of the cutting until it succumbed to expanding landslides, it has also sometimes been known as the Gaillard Cut in memory of David Gaillard who was chief engineer on site throughout its excavation.

For a large proportion of its 5 km length, the Culebra Cut required excavation down to depths of about 50 m below original ground level. The original plans called for steep rock walls with a rim width of little over 200 m; but matters evolved when the canal was made wider and the excavated faces flared out with repeated slope failures and landslides until parts of the cut reached widths of 1500 m (Fig. 5). 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. Hundreds of large steam-powered drills bored holes into which were planted a total of 3000 tonnes of dynamite to blast the rock into fragments that could be excavated by rail-mounted steam shovels. More than 100 km of railway tracks were moved about on multiple benches within the cut and also extended to the main tip site that created new land from the shallow sea beside Panama City. Only in the later stages could

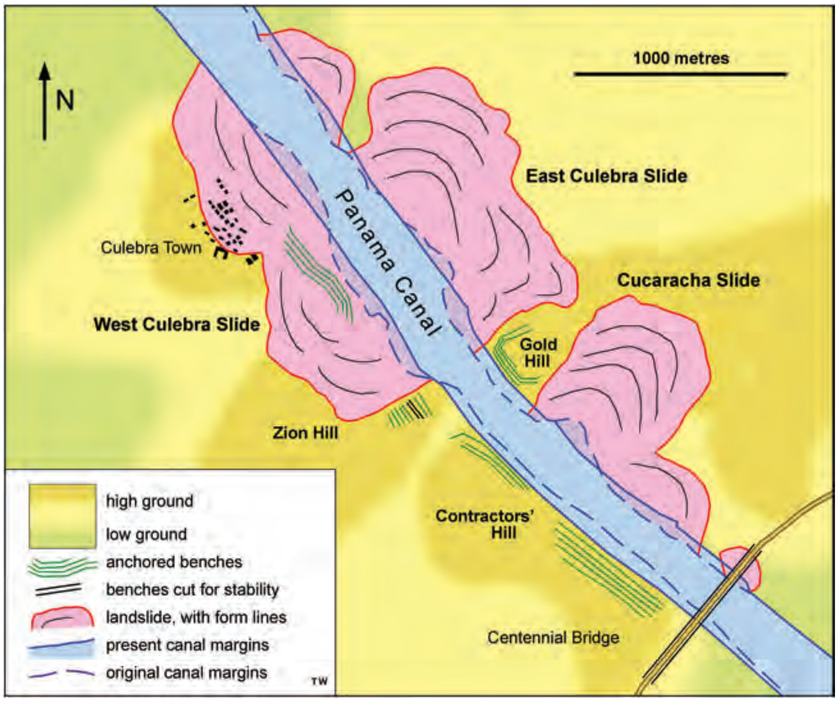

Fig. 5. The main landslides and hills along the Panama Canal's Culebra Cut.

Fig. 6. An innocuous canal-side exposure of clays in the Cucaracha Formation.

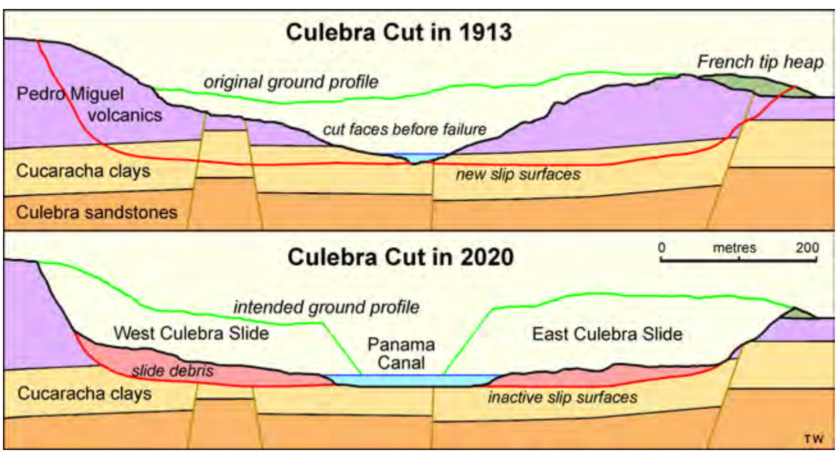

Fig. 7. Simplified cross-sections of the Culebra Cut looking towards the northwest, in 1913 and therefore late in the construction phase, and also as now after development of the two large landslides and the removal of most of their slipped debris.

large floating dredgers and barges be brought to the task in intentionally flooded excavations.

Three Neogene rock formations dominate the geology of the Culebra Cut. As might be expected, the highest ground was largely formed of strong rock. Much of the excavation was therefore in the Pedro Miguel Formation, which consisted of andesites, tuffs, agglomerates and various other volcanics, 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 (Fig. 6), and beneath them 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.

Critical stages were reached within the Culebra Cut whenever and wherever excavations through the volcanic rocks reached down into the underlying Cucaracha clays (Fig. 7). This allowed extensive shear surfaces to develop within the clay, and the three large and famous landslides crept into activity while engineering works were still in progress (Fig. 8). 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 certainly 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 10 m above slip surfaces that curved upwards to the surface. The landslides could therefore be described as rotational, but did not have the circular profiles that can develop in homogeneous material.

Cucaracha clay

Subsequent analyses of the Cucaracha clay have shown it to be amazingly weak. This is largely because its dominant mineral is smectite, that is, the weakest and least stable of all the clay minerals. Clays are ultimately derived from the weathering of silicate rocks, and smectite is the type that dominates in the weathering of volcanic rocks in hot and wet tropical conditions. Parts of the Cucaracha Formation are recognizable for their ash content, and the sequence does include one bed of ignimbrite; it is likely that much of the clay has an ash content or is derived from weathering of the region's volcanic rocks that preceded the Pedro Miguel

Fig. 8. An early stage of development of the large Cucaracha Slide. Most of the slide debris consists of Cucaracha clay, but the broken rock in the centre of the view is largely volcanic material from the adjacent face of Gold Hill.

Formation. 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 in Cucaracha clay is its major decline in strength due to restructuring when it is deformed. Shear stress is imposed by differential loading within the geometry of a slope profile, and may overcome the strength of the rock at a value known as its peak strength. Then, where the induced strain and deformation within the rock includes realignment of its minerals, shear planes can develop more easily, and the strength of the rock 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 percent of its peak strength. Consequently, landslides that started within the Culebra Cut were bound to continue moving due to the declining strength in their basal layers and indeed were likely to expand as further parts of the slope were overstressed and destabilized.

This concept of strain softening and residual strength was not understood in the 1910s, so neither the cause of the landslides nor their potential for increasing scale could be fully appreciated. The landslides in the Culebra Cut were too large and too structurally complex to be stabilized, so the engineers took the only available option of letting the slides run and removing the debris as it arrived (Fig. 9). This was where the massive machine capability of the Americans proved to be invaluable, and brute force really did win the day.

With the incessant creep of the Culebra Cut's landslides, the canal was allowed to fill with water ahead of schedule, so that floating dredgers could be brought in with their greater capacity for removing the slide debris as it arrived. This action was also justified, at the time, by the mistaken concept that water within the canal could provide some support for the landslide masses. The engineers saw reports from excavations at Gatun indicating that the counteracting weight of water tended to hold slides in check. In fact, this was a mistaken concept, as any increase in pore-water pressure (or in joint-water pressure), due to rising water table or adjacent impounding, is the prime means of inducing slope failure. Groundwater pressure causes partial floating of the rock mass, thereby reducing frictional resistance to shear failure; this is the now-well-known concept of effective stress. It is likely that some whim of geological structure at a single site at Gatun had created a situation open to false interpretation. However, the misguided flooding of the Culebra Cut might have had benefit in that it must have accelerated the inevitable landslide movement and thereby allowed earlier clearance of its debris. Perhaps by chance, the engineers got it right.

Fig. 9. An early stage of the East Culebra Slide, in 1913, before continued slumping and toe removal left a much lower profile on this bank of the canal.

Continued activity of the landslides

Landslides in 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 15 August 1914, though small company ships and tugs had been passing through for some months 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, but that was only when the canal was not closed by the on-going landslides. 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 unusually massive Panama Canal excavations. Wet-season failures of clay slopes and small rockfalls were almost routine events. The response could only be further excavation to reduce slope angles, and many of the excavations soon exceeded their planned widths. Some rather larger failures occurred where the complex, variable and unpredictable geology allowed blocks of hard rock to slide into the excavations; faulted margins and underlying clay beds were characteristic of the failed blocks. Then the dimensions

Fig. 10. The West Culebra Slide when successive slices were falling away from the head scarp, thereby undermining and destroying the small hill-top town of Culebra.

of these failures were hugely surpassed by some very large landslides.

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. 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. The clay was too soft to be excavated by the steam shovels, and was therefore largely removed by sluicing it with water from a high level and then picking it up with floating dredgers. The Cucaracha Slide moved again and temporarily closed the canal in 1920, and parts of it were also reactivated in both 1972 and 1986.

There had been small failures and movements of parts of the West Culebra and East Culebra Slides for some years before their really large displacements started in 1914. This was soon after the canal had been opened to shipping, and their debris closed the canal for much of 1915. By then, most of the small hill-top town of Culebra had been carried away by the West Culebra Slide where its head scarp had retreated and enlarged the slide in a series of events (Fig. 10). 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. They were the classic deep-seated slides with larger masses of the hard volcanic rocks moving on slip surfaces within the underlying clay (Fig. 7). In the long term, these displaced greater 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 m from the canal banks. Widening of the canal during the 1950s also included some re-profiling of the lower slopes. 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. Dredgers were seen in action in 2012 and 2016, but not in 2020 (Fig. 11); it appears that the ground is slowly approaching a stable state.

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. 12). It is stable, and the few rock-bolts visible on its faces represent only minor, localized, safety measures.

In 1954, a widening head crack was found on Contractors' Hill. Stability was recovered by excavating a long, man-sized, drainage tunnel behind the face and also terracing the setback on the lower part of the slide. More recently, the rock spur of Zion Hill that forms the southern flank of the West Culebra Slide 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. 13).

Widening the canal

Improvements to the canal included a protracted phase of widening during the 1950s. This could not make major changes to the big rock faces in the Culebra

Fig. 11. A floating suction dredger in front of the West Culebra Slide in 2012, with its suction pipe and rotating head raised out of the water while not in action.

Fig. 12. The Canal's classic view of Gold Hill with the Centennial Bridge beyond. Though the terraced rock face of Gold Hill is the conspicuous feature, the low slopes on the left are actually more remarkable as they are all that is left after removal of most of the very large East Culebra Slide.

Fig. 13. On the left the anchored wall that has stabilized its rock buttress of Zion Hill after it was seen to be creeping over underlying clay. To its right, the West Culebra Slide has been cut to a much lower profile and is now largely stable, though a floating dredger was working at its toe when this image was taken in 2012.

Cut (Fig. 14), 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). One other new feature was the Madden Dam, completed on the upper Chagres River in 1935. The impounded Lake Alajuela 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 widening of the locks. A major event in the canal's history occurred at the end of 1999 when the USA relinquished control of the Canal Zone, by handing the canal and its infrastructure over to the state of Panama. New large container ships were already taking over in 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, and 76 percent 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 canal's future income.

Yet again, construction at Panama became another giant piece of civil engineering. It used more than seven million tonnes of concrete, but all was 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-m-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 for most smaller ships (Fig. 15).

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

Fig. 14. Gold Hill in profile, with the broken ground of the Cucaracha Slide occupying the entire foreground.

were copied from designs on Belgian locks. Each lock is also accompanied by a multi-level set of water-conservation basins, which allow 60 percent 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. Palaeogene sandstones and mudstones that are strong and massively bedded allowed steep faces to be cut for the lock excavations, and these remained stable prior to backfilling around the concrete structures (Fig. 17).

Fig. 16. The new Agua Clara Locks each with their three water-conservation basins. (Photo by Panama Canal Authority.)

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 beyond them passes beside the Miraflores Lake that lies 11 m below and extends as far as the Pedro Miguel Locks. The new canal is therefore retained behind the Borinquen Dam that is 2300 m long where it overlooks the Miraflores Lake. Effectively forming the canal bank, the dam has 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 dam stands on adequately strong sedimentary rocks, but these are

Fig. 15. Old and new locks out of Gatun Lake at the Atlantic end of the Panama Canal. The Earth components of the Gatun Dam are the entire areas covered in paler green grass, with the curved crest of its concrete spillway at the centre above the Chagres River. (Base images from GoogleEarth.)

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 dam nor the concrete lock structures.

The expanded canal has already proved to be a great success for the Panama nation, and the new lock dimensions assure its future (Fig. 18). There are already 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 China to Europe, but this would only be for a part of each year.

Before the Panama Canal was enlarged there was some enthusiasm for a return to the old concept of a larger canal through Nicaragua. To this end, a Chinese company was established in 2012 and was loud in its promotion of the project, with ground surveys and initial planning. But plans were forestalled by completion of the new Panama locks, and the company quietly disappeared in 2018. 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 m above sea level. Of some interest 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.

Fig. 18. Weighing in at more than 150 000 tonnes, a fully loaded Neopanamax container ship sailing at some 26 m above sea level on Gatun Lake.

Fig. 17. An early stage of construction of the Agua Clara Locks, with the excavations bounded by steep faces cut into stable Palaeogene sedimentary rocks. (Photo by Panama Canal Authority.)

Suggestions for further reading

Bennett, I. 1915. *History of the Panama Canal*. Historical Publishing, Washington, DC, USA. www.czbrats.com.

Lutton, R.J., Banks, D.C. & Strohm, W.E. 1979. Slides in Gaillard Cut, Panama Canal Zone. Voight, B. (ed). *Rockslides and Avalanches*, chap.4, v.2. Elsevier, Amsterdam, the Netherlands.

Maurer, N. & Yu, C. 2011. *The Big Ditch: How America Took, Built, Ran, and Ultimately Gave away the Panama Canal*. Princeton University Press, Princeton, NJ, USA.

Panama Canal Authority 2006. *A History of the Panama Canal*. www.pancanal.com/eng/history.