

Going South: Analysis of an Historic Project Engineering Failure

John H. Scott*

NASA Lyndon B. Johnson Space Center, Houston, TX, 77058

NASA's successful conduct of the Apollo Program greatly enhanced the prestige of the United States and remains broadly accepted as America's gift to all Mankind. NASA's accomplishments continue to amaze the world. With the Vision for Space Exploration (VSE) Americans once again tasked NASA to carry out a project that is expected to provide inspiration and economic stimulus to the United States and to the world. In preparation NASA has thoroughly examined space program precedents. There is, however, another precedent which has not been examined in this context but whose scope and environment in many ways parallel the VSE. This project was initiated by a team that had, ten years before, successfully completed an effort that, at a cost of \$173 billion (in 2008 dollars), had pushed the envelope of technology, brought economic growth, established their country as the world leader in engineering, and been broadly accepted as that country's gift to all Mankind. The new project was again inspired by popular desire to enhance national prestige and make yet another major contribution to Humanity. This effort was predicted to require eight years and \$156 billion (2008 dollars). However, after nine years and expenditures of 96% beyond the baseline, the project collapsed amid bankruptcy, political scandal, and criminal prosecution. This paper applies current project management metrics, such as earned value analysis, to review the strategic decisions in this historic failure and describe its ultimate collapse. Key mistakes are identified, and lessons are drawn which may prove useful in guiding the VSE.

Nomenclature

\$	=	United States Dollar
Fr	=	French Franc
m ³	=	cubic meter
km	=	kilometer

I. Introduction

THIS paper analyzes the development and conduct of the 1879-1889 effort of the French corporation *Compagnie universelle du Canal interocéanique de Panama* (hereinafter called "the *Compagnie*"), led by Ferdinand de Lesseps, to construct the Panama Canal. Ten years before the 1879 formation of the *Compagnie Universelle*, another company made up of the same program management team had successfully completed the Suez Canal, bringing great prestige to France in the eyes of the world and substantial profit to its shareholders. Thus, when the political and financial environment appeared to offer the opportunity to carry out another such effort, Ferdinand de Lesseps again engaged the same team to initiate the effort and attracted investment capital based on an estimate that the canal would require 8 years and Fr 600,000,000¹ (\$156 billion 2008[†]) to complete. By the time of its 1889 bankruptcy the *Compagnie* had excavated only 53,000,000 m³ out of the 75,000,000 m³ assumed for the cost baseline^{2,3} (and of the 200,300,000 m³ finally required to make the canal operational in 1914⁴) and had burned through Fr 1.18 billion⁵ (\$269 billion 2008) and approximately 16,500 lives⁶.

Many modern historical analyses of this effort^{7,8,9}, taking their lead from the assessments promulgated by contemporary U.S. media outlets¹⁰ and by the French government's tribunal of 1892¹¹, hold that this project was doomed from the beginning due to manipulation by French financiers of the generally delusional thinking and extremely persuasive rhetoric of Ferdinand de Lesseps himself. An engineering analysis of this project reveals, however, a somewhat different picture. The *Compagnie*'s effort was certainly set on a course to failure early on. However, this was brought about due to certain strategic decisions on the part of the project leadership that were carefully considered and, as events would show, wrong. First, project management misread the attitude of their stakeholders and thereby deliberately underestimated the project's cost, at a point when such "low-balling" was

* Chief, Energy Conversion Branch, Mail Stop EP3. Member, AIAA

† See Appendix I for value and currency escalation methods.

completely unnecessary to sell the project. Second, project management failed to recognize the need for a certain technology program, which would have been within the technical and financial means at their disposal and which turned out to be critical to the success of the effort. Such mistakes can lead to the demise of a project of any technology and are relevant considerations for the leadership of any large engineering effort.

II. The Project Environment: Politics and Engineering

A. Politics: France in the World 1869-79¹²

The opening of the Suez Canal in 1869 “made” Second Empire France in the eyes of the world. Though carried out as a commercial venture (albeit with considerable support from the government of Egypt) that quickly became profitable, the canal was lauded internationally as having been done “for the well-being of Humanity[†]”. It was seen as a triumph of finance capitalism and exemplified the power of France to spread western civilization to the Middle East and Asia. The canal also conveyed to France the gates of what quickly became the world’s busiest trade route and the strategic lifeline of France’s recent ally and ancient rival: the British Empire (a fact which motivated significant British opposition to the project throughout its development, followed by British military occupation of the canal zone in 1882). The project’s entrepreneur, diplomat Ferdinand de Lesseps, achieved the status of a national hero in France: “The Great Frenchman[§]”.

However, within two years of the opening of the Suez Canal, came what is known in French culture as “The Debacle^{**}”: the 1870-1871 series of events starting from France’s defeat in the Franco-Prussian War, through the fall of Napoléon III, the formation of the Third Republic, and the civil war over the Paris Commune. Troops of the new German Empire occupied parts of France to force payment of an indemnity of Fr 5 billion (\$1.9 trillion 2008). Nevertheless, the French people and economy recovered quickly from these disasters. The war indemnity was paid off by 1873 (two years early), and the economy boomed. In fact, the economy grew so well that the Paris stock market (hereinafter referred to as the “Bourse”) ^{††} was relatively unaffected by the global (United States and Europe) economic depression that started with the Panic of 1873. While the depression notably slowed traffic growth in the Suez Canal¹³, briefly impacting the market capitalization of the operating company, by the beginning of 1879 the Bourse had for four years been gaining at a steady 4%.¹⁴ There was a broad political will to leave “The Debacle” behind and show the world that France was “back.” Finance capitalism and an unfettered private sector were seen as the keys to such progress. It was in this environment that a syndicate of investors was formed in France to develop a project for a canal through the isthmus of Central America. This syndicate funded some preliminary surveys and obtained a concession from the Columbian government to build a canal through what was then the Columbian province of Panama.

The economic and strategic value of an American isthmian canal was not lost on the United States (or Great Britain) from the time of the 1849 California “Gold Rush” and the 1850 opening of Japan. The Clayton-Bulwar treaty bound the United States and Great Britain to joint control of any canal through the Central American isthmus at Nicaragua.

B. Engineering: Megaprojects, Technology, and Disease in the 19th Century

The Suez Canal project earned for France the reputation as the world center of engineering and technology. Design studies financed by the Egyptian government and French private investors in 1855-6 developed a baseline design for a canal at sea level to be built with railroad-supported hand labor (provided by the Egyptian government under a system not unlike that of the ancient Pharaohs) for Fr 162 million.¹⁵ Financing was obtained on the Bourse, and construction began in 1859. Employing up to 20,000 workers, excavation along the main canal axis averaged 500,000 m³ per month in 1862. However, British agents began to agitate unrest in the workforce early on, and the Egyptian authorities began to withdraw their people in 1864. A cholera epidemic hampered the workforce further in 1865-6. Costs mounted, and debt financing became required, forcing the issuance of lottery bonds. In response, the project office motivated the prime contractors to search for new technology.¹⁶ Prime contractor Couvreux & Hersent responded by funding further development of a steam ladder dredge that had been invented by Combe & Co. of

[†] ...pour le bien de l’Humanité

[§] *Le Grand Français*

^{**} A French novel, *La Débâcle*, by Emile Zola is set during this period.

^{††} *La Bourse de Paris*

Lyon in 1859. The dredges began to come on line in 1865.¹⁷ Excavation rates passed 860,000 m³ per month in November 1866 and averaged 1,737,935 m³ per month in the year before the canal became operational in November 1869.¹⁸ The final cost of the canal came in at Fr 433 million, representing an overrun of 167%.¹⁹ The experience of the Suez Canal would weigh heavily in the development of the *Compagnie Universelle* effort in Panama.

The engineers who built the Suez Canal and many other large projects in and managed from France were in general products of the *Ecole Polytechnique*. Founded by Napoléon I with the motto “*pour la Patrie, les Sciences, et la Gloire!*,”^{††} the *Polytechnique*’s curriculum focused heavily on the fundamentals of mathematics and classical mechanics and was believed at the time to produce the best trained engineers in the world (It is still highly regarded).²⁰ Such confidence was not misplaced. The 1855 design study developed by *Polytechnique* alumni for the Suez Canal predicted, based on surveys, core samples, and engineering judgment on the stability of cuts in various types of soil and rock, that the canal would require excavation of 74,639,132 m³.²¹ The canal became operational after excavation of 74,141,893 m³.²²

Another 19th century project which played into planning for the French Panama effort was the Panama Railroad, built across the Isthmus of Panama from Colon to Panama City. Begun in 1850 by an American business syndicate in response to demand from the California “Gold Rush”, the railroad was initially estimated to cost \$1.3 million and to take two years to build. The effort required five years and \$8 million (500% overrun), along with (at least) 6,000 lives. The primary issue was yellow fever, though a cholera epidemic played a significant role as well. People in the United States were horrified by this, so much so that the syndicate plainly lied about health statistics during and after construction. Statistics were poor to begin with, as death records were only kept for the less than 10% of employees who were of European heritage. Deaths among West Indian African-heritage laborers were not counted. Nevertheless, the railroad earned \$7 million in profits during its first six years of operation, paying an average 15% dividend to shareholders.²³ The fact that this project had become a financial success despite the unexpected cost in lives and capital would be noted by the *Compagnie* leadership.

The Panama Railroad experience also reveals the understanding of tropical diseases, such as yellow fever and malaria, extant during the late 19th century. Yellow fever had for centuries brought particular dread to Europeans. An epidemic in 1798 decimated a French army in Haiti, leading Napoléon I to give up plans for an American empire and sell Louisiana to the United States. At the time of the Panama Railroad project, such diseases were generally understood to be caused by toxic fumes emitted from tropical soil when disturbed, hence the epidemic brought about by building a railroad through such an area. After Pasteur’s germ theory of disease began to take hold in the 1860’s, there was some belief that these diseases might be brought by aerobic bacteria bred in swamps or in cities with poor hygienic conditions. However, as early as 1848, physicians in the United States and the tropical colonies of Europe published findings linking the spread of yellow fever and malaria much more strongly to the mosquito rather than to any airborne toxin or bacterium. Presentation of this theory to Spain’s Royal Academy of Sciences in Havana occurred in 1881. This theory would not be acted upon until the United States Army decided it was unwilling to accept the massive yellow fever casualties experienced among troops in Havana in 1900, whereupon it would be quickly proven correct.²⁴

III. The Architecture Congress and System Requirements Review (SRR)

The French syndicate promoting investment in a canal through the Central American Isthmus, now led by Ferdinand de Lesseps, invited engineering and financial experts from around the world to the International Congress for Studies of an Inter-oceanic Canal^{§§} (hereinafter referred to as “the Congress”) in Paris in May 1879. The stated purpose of the Congress was essentially that of a modern SRR: to obtain a consensus on the layout of a canal that would operate at a profit and attract development capital internationally.

The Congress ran for two weeks, involving five different subcommittees, and carried out trade studies among five potential routes, with sometimes multiple design solutions for each (See Fig. 1). Each route also had a distinct political advocacy, and many of the options had been discussed for decades, if not centuries. The Congress’ discussions centered on two primary products: (1) the development of traffic models by which to judge the potential for toll revenue of a given design solution and (2) assessments of technical risk and cost for each design solution.

Traffic model assessments noted that the chief competition for the canal would not so much be the sea route around Cape Horn as the bimodal (ship-railway) routes involving the transcontinental railroads then extant and under construction in North and Central America. The subcommittees engaged in the issue concluded that the canal would not be at all competitive with this alternative for passenger and high value cargo traffic and must offer a time

^{††} “...for the Homeland, the Sciences, and Glory!”

^{§§} *Congrès International d’Etudes du Canal Interocéanique*

savings between the respective coasts of the Americas and between Europe and Asia/Australia to be highly competitive with the railroads for bulk cargo.²⁷ Seen as key to the management of bulk cargo transit was its seasonal nature. Thus, while their rough calculations indicated that the canal needed only to support 8 ships/day on average (for 7.5 million tons/year of traffic), traffic during wheat harvest season could peak at 50 ships/day, and variable weather conditions could raise the arrival rate at either terminus beyond even that. A locked canal was deemed capable of, at most, 24 ships per day, and shipping firms would shift to bimodal options if wait times of more than a few days were to be consistently encountered.²⁸ The experience of traffic growth at the Suez canal was also considered. It was noted that the Europe-India route offered by Suez, never far from shore, had actually made coal-fired steam more competitive with sail, which had in turn stimulated investment in steam technology to the point that marine steam engine designs had tripled in efficiency since Suez had opened. Traffic growth through Suez had been slow at the start because shipbuilders had not seen such investment as worth the risk until the canal had actually become operational. An analogous, though unpredictable, technology impact was projected from the new canal being considered.²⁹ Finally, it was noted that, despite the recent improvement in steam fuel efficiency, coal fired steam was still not competitive with sail for the growing, tradewind-driven route from Europe to Australia and Asia. The canal thus had to efficiently allow passage for sailing ships.³⁰ Anything but an open, sea level canal was seen as putting this capability at risk.

The technical subcommittee considered fourteen design solutions among the five routes. The fidelity of the plans presented ranged from almost aerospace Preliminary Design Review (PDR)-level to what modern engineers would consider “viewgraph engineering.” Cost estimates were based on excavation volumes calculated with generally accepted “rules of thumb” regarding the slopes required for stable walls in various strata. Discussions quickly narrowed down to two solutions. One, supported by PDR-level surveys and hydraulic calculations and advocated by both the senior U.S. Navy delegate and a prominent French engineer, involved a 290 km route through Nicaragua, incorporating a navigable river and a large lake at 32 m elevation, which would be reached by multiple flights of locks (See Fig. 1, note A). The other, presented with little supporting data and advocated by engineers in the employ of the syndicate, involved a 55 km sea level route following roughly that of the Panama Railroad and incorporating an 8 km tunnel cut through a range of hills that reached 87 m elevation at the lowest pass at a place called Culebra (See Fig. 1, note B). The Nicaragua route was judged to have low construction cost (See Fig. 1 table for cost figures) and to present less disease risk to the workforce. The primary criticisms stemmed from the region’s perceived susceptibility to seismic activity and the design’s relatively long transit and risky lock operations. The Panama solution was criticized for being presented with little survey data, making it difficult to render a cost estimate. While the short transit time was seen as a great advantage, operations in the tunnel were noted as very risky (particularly for sailing ships), the extreme fluctuations in the flow of local rivers would hamper construction and silt up the canal, and (most important) disease risk was perceived as much higher than with the Nicaragua route. This was judged to be the most expensive of the major options. A third design solution was developed during the discussions in an attempt to capture the best aspects of the two leading designs. A prominent French engineer (Godin de Lépinay) presented a concept, judged to require half the time and just over half the investment of the Panama sea-level option (See Fig. 1, Note C), whereby the main river on the Panama isthmus would be dammed to create a navigable lake at 25 m elevation, reached by flights of locks and thereby turn the negative of the river into a positive.^{***} It was noted that, even in this case, the cut required through the hills at the pass would be 72 m deep, 12 m deeper than any known precedent.^{31, 32} Whether the “rules of thumb” regarding the slope of the cut’s walls would apply to a cut of such depth was not questioned.

The debate continued into the general sessions of the Congress, where the traffic model’s estimate of 7.5 million tons/year was heavily criticized as overoptimistic. Ferdinand de Lesseps himself called the question by claiming persuasively that the traffic model required a sea level solution. The syndicate that had organized the Congress, which would later be absorbed into the *Compagnie*, was accused by American media outlets of having attempted to orchestrate attendance in order to validate their plan, already negotiated with Columbia, to place a canal in Panama.^{33, 34} To whatever extent this was true, the syndicate was not fully successful at doing so. The Congress was structured to require a vote on the basic requirements of the canal and close the SRR, and when the Panama sea level option was called up, 78 of the 138 delegates voted for it. Of the remaining, 8 voted “no” (including *Polytechnique* alumni de Lépinay and Gustave Eiffel), and the remainder either abstained (as the U. S. Navy delegation did) or did not appear.³⁵ In the statement accompanying his “no” vote, de Lépinay opined that, based on his experience in the tropics, the Panama sea-level project would fail due to the impact of disease on the workforce.³⁶ Nevertheless, judging predications of the traffic model to justify the expense and risk, the Congress

^{***} This is almost exactly the solution chosen by the United States Isthmian Canal Commission in 1907.

reported out a recommendation for a sea-level canal through Panama, projected to cost (with 25% margin and allowance for the cost of capital) Fr 1.2 billion, require 47,000,000 m³ excavation,⁴⁰ and take 12 years to construct.

IV. Preliminary Design Review (PDR) and Financing the Project

The project management team formed the *Compagnie Universelle* and retained lead Suez contractor Couvreux & Hersent as prime contractor. The team understood that they had a challenging task ahead, and they pursued it with full knowledge that the reputation of their country was riding on their performance. However, the reaction of the management team to the first setback would set them on the road to failure.

In August 1879 with seed capital from the syndicate, the *Compagnie* floated an initial public offering (IPO) on the Paris Bourse for Fr 400 million (a third of the projected cost of the effort). The plan was to finance the rest of the effort through bonds, as had been done with Suez. This was done without engagement of the marketing services of the major investment banks. This technique had been used for the Suez IPO with success at a much lower cost than the 5% placement fee then quoted by the banks³⁷. The IPO failed. The management team's initial assessment attributed the failure to (1) their decision to not use the services of investment banks, (2) an admittedly accurate public perception that the design was immature (Suez's design had been beyond PDR-level before its IPO³⁸), and (3) a public perception (also not unreasonable) that the toll revenue projected by the Congress' traffic model might not bring a compensatory return on a Fr 1.2 billion investment.³⁹

To remedy this, both prime contractor Couvreux & Hersent and a consulting engineering commission were engaged to develop PDR-level designs and "improved" cost estimates. The consulting commission's work started in December 1879, involved surveys and borings along the route recommended by the Congress, and was reported out in February 1880. Their recommended design required an open cut through the Culebra pass (with walls sloped at 1^{horiz}:4^{vert}, See Fig. 2a), required a minimum waterline width of 28 m, allowed tighter curves than the Congress' design, and proposed damming the unstable Chagres river above the canal and cutting diversion channels to keep flooding away from the canal axis. This PDR design would require 75,000,000 m³ of excavation (higher than the Congress estimate due to the open cut), would (with margin lowered to 10% and ignoring the cost of capital) cost Fr 843 million, and would take only 8 years to complete. The *Compagnie* management believed further economies might be expected and opined an estimate of Fr 646 million.⁴¹ In May, the parallel study by Couvreux & Hersent yielded an estimate, stated to be conservative, of Fr 530 million⁴⁹ to which the *Compagnie* management later added allowance for cost of capital to yield a total cost of Fr 600 million. Thus, by the time they announced another attempt at an IPO in November 1880, the *Compagnie* had lowered their projected cost by 50%, to a level which they advertised would yield attractive returns from the tolls projected by their traffic model.⁴² Further, the *Compagnie* engaged several large investment banks to market the issue.

The second IPO went out in early December 1880 for Fr 300 million, this time 50% of the estimated total capital required (in order to appear to lower risk). It was wildly successful, being oversubscribed by 100%. Even more notable, 82% of the issue was bought by French citizens who would hold between 1 and 5 of the 1.2 million shares sold,⁴³ making the project a political issue in France.^{†††} This "success" came at a huge price. First of all, between the commissions exacted by the banks, the cost of advertising, and the value of the "founders shares" provided free to members of the syndicate and to executives of those banks, the issue had cost Fr 32.2 million (or more than 10% of the yield). However, the greatest cost of the IPO to the effort was the lost opportunity. The "low-balling" that the project office implemented, cutting 50% from the already uncertain estimate, was completely unnecessary to raise capital. In the year leading up to the first IPO attempt in August 1879, the Bourse had gained 6%, while Suez shares, with which the *Compagnie* management was inextricably associated, had actually fallen by 2%. The Bourse was thus fundamentally unfavorable for an IPO by what was essentially the Suez team. However, in the 15 months from the first IPO until the announcement of the second in November 1880, the Bourse had gained 13% annualized and Suez stock had skyrocketed at 60% annualized (investors possibly noting a recovery of world shipping from the depression that had begun in 1873⁴⁸).¹⁴ These statistics and the massive oversubscription to the IPO that did go forward indicate that the *Compagnie* could have kept to the Congress' Fr 1.2 billion estimate, ridden the wave, and raised Fr 600 million or more. The project leadership may or may not have initiated their Panama effort with inadequate attention to technical risk. They certainly did not pay attention to the stock market.

^{†††} *Compagnie Universelle* shares would be held by 0.25% of the 1880 population of France, making them three times more widely held than any other stock in France at the time. For perspective, the most widely held security in the United States as of this writing is that of Prudential Financial, whose 2.4 million shareholders make up 0.8% of the current population.⁴⁷

V. Initial Progress and the Critical Design Review (CDR)

The *Compagnie* organized itself and initiated work in Panama in February 1881, three months after the IPO. There would be an “up and out” corporate office in Paris and a larger “down and in” project management and engineering office in Panama City. The *Compagnie* set up a standing review board of noted engineers in Paris (*La Commission supérieure consultative des travaux*, hereinafter referred to as “the Review Board”) to perform periodic technical reviews. A two year, cost-plus contract was let to Couvreux & Hersent to begin installation of infrastructure, carry out experimental excavations at various points so as to estimate appropriate unit prices for a cubic meter of excavation in the various soil conditions, and generally bring the design to what would in modern times be considered a “CDR” level. Plans were for the *Compagnie* and Couvreux & Hersent to form a joint venture to carry out the work proper once this preliminary effort was complete. Also in March 1881, in order to assure priority for the transport of spoil, the *Compagnie* purchased a controlling interest in the Panama Railroad.⁵⁶

The concerns about disease voiced during the Congress clearly got the attention of the *Compagnie*. While their “up and out” media campaign in the *Bulletin du Canal* had belittled the risk from the start,⁵⁷ records of internal management discussions reveal a consistent humanitarian concern for protection of the employees.⁵⁰ More telling by far is the investment made by the *Compagnie* in hospital facilities. The Fr 30 million cost of the central facility represented 40% of funds, facility and operations, spent in Panama during the first three years of activity.^{51, 52} The hospitals were staffed by some of the best professionals France had to offer and would be considered by contemporary American health officials as the finest ever created in the tropics up to that time. However, the investment was mostly wasted, as design of the health care system was based on the theory that yellow fever and malaria were spread aerobically. The hospital landscaping actually bred mosquitos.⁵³ The author can find no record that the August 1881 presentation of a theory of transmission via mosquito to the branch of Spain’s Royal Academy in Havana⁵⁴ was ever noted by *Compagnie* medical or managerial personnel, even though professional personnel must have been recruited from that city. The fevers began to tell early. By the end of 1882, when only 3,800 employees and contractors were working on site, *Compagnie* hospitals had recorded 106 deaths from yellow fever and malaria.⁵⁵ As only *Compagnie* employees and senior contractor employees had access to the hospital system deaths among the contractors’ labor workforce were not recorded.

The risk perceived in the project began to mount. The cash position of the *Compagnie*, impacted by the Fr 35 million down payment on the Panama Railroad shares, forced the issue of Fr 110 million bonds in September 1882. The issue sold fully, but underwriting and publicity fees ran 7%,⁵⁸ rather than the customary 2%.⁵⁹ Then, in December 1882, prime contractor Couvreux & Hersent decided to not take up their contract option to continue the work. They did so without any public statement regarding their reasons. The influence that the malaria death a month prior of their on-site project director may have had on this decision is not recorded.⁶⁶

With the prime contractor’s departure, the *Compagnie* sent a project director, *Polytechnique* alumnus Jules Dinger, to take direct control of the effort in Panama. His team arrived in March 1883, worked aggressively (spending a lot of time on the employee health care system),⁶⁰ and had a CDR-level design by July. This was presented to and approved by the Review Board and the *Compagnie* shareholders in Paris in September 1883.^{61, 62} The design (see Fig. 3) kept the PDR concept of an open cut and a dam on the Chagres river. The Chagres and other rivers were to be diverted from the canal axis by means of channels cut, in many places, parallel to the canal axis and separated from the canal by dykes made of spoil (See Fig. 4b).⁶³ The Chagres dam at Gamboa, was to be a gravity dam built up of spoil and would feature a spillway sized to limit flow to what could be contained in the diversions (see Fig. 4a). The walls of the cut at Culebra would require a 1:1 slope for stability (less steep than assumed at PDR – See Fig. 2b). A total excavation of now 120,000,000 m³ would be required, but the post-PDR Fr 600 million cost estimate was maintained.⁶⁴ In support of a bond issue set for October 1883, *Compagnie* “up and out” executives had begun claiming that work on the canal would accelerate so as to allow opening during 1888, or 4.5 years after CDR and a full year earlier than had been projected at PDR.⁶⁵ However, there is no record of Dinger or the “down-and-in” project office ever having planned for an 1888 completion.

VI. CDR Forward

Fig. 5 plots the project excavation progress and earned value performance against the financial and disease environment from the formation of the corporation in January 1881 through the end in early 1889. Going from the top down, the financial environment line (Fig. 5a) tracks the performance of the *Compagnie* equity shares against the CAC 40 index of the Paris Bourse.¹⁴ The share price is indexed to the CAC 40 at the par value, and bond issues are also identified. The earned value chart (Fig. 5b) plots cumulative Actual Cost of Work Performed (ACWP), Budgeted Cost of Work Performed (BCWP), and Budgeted Cost of Work Scheduled (BCWS) starting from CDR in July 1883 until work halted in January 1889. (See Appendix II for earned value calculations.) The monthly

excavation chart (Fig. 5c) tracks the scheduled excavation volume (used as the basis for BCWS) against actual excavation volume⁶⁷ on a monthly basis, again starting with CDR in July 1883. The death rate and population chart (Fig. 5 d) tracks an index of the death rate (deaths in the *Compagnie* hospital system) from mosquito-borne disease along with an index of the total population of employees on site.^{†††} It should be noted that, while it is evident that the project office did have an expected monthly excavation rate that would achieve the required spoil removed by the planned 1889 opening of the canal,⁷³ no copy has been found by the author. It can be inferred that they were expecting progress on the pattern of the Suez project, with a slow start followed by technical innovation enabling substantial increases in excavation rates later on. At Suez the monthly rate near completion came in at four times that of the earlier work. Thus, an analogous progression has been assumed by the author.

Inspection of Fig 5, gives a good indication of the overall status of the project as of CDR. The stock had begun to mildly outperform the market. In total (including cost of capital and purchase of the Panama Railroad), the *Compagnie* had invested Fr 240 million. The project office kept project management in the hands of *Compagnie* employees to a rather low level, continuing the pre-CDR practice of engaging numerous small contractors to experiment with different means of excavation along the route.⁷⁴ Heavy equipment was arriving, and manpower stood at 6,200. There was a large contingent of European and American engineers and equipment operators and a rapidly growing contingent of West Indian (mostly Jamaican) laborers for the extensive handwork. The *Compagnie* had made a conscious decision to recruit such people (as opposed to the Greek or Italian laborers at Suez) for the better part of the hand labor, as the medical consensus indicated that they were more likely (but far from certain) to be immune to yellow fever, to which it was thought people in the diggings would be more exposed than those in the offices.^{§§§} Yellow fever and malaria deaths (in hospital) as of CDR totaled 205. While there had been a spike the previous summer, the rate did not pick up as expected during the peak of the June-through-November rainy season and had even slowed considerably. In sum, the *Compagnie* team in Panama was educated, experienced, and had every reason to think they would succeed.

Work did pick up apace. Excavation rates of better than 500,000 m³ per month, probably on plan for that period, had begun by January 1884. A U.S. Navy officer who inspected the project at this point rendered a positive report to Washington DC.⁶⁹ The *Compagnie's* shares continued outperforming the Bourse index. Construction equipment on site consisted of dredges for the marsh and entrance areas and steam excavators, similar to those developed for the Suez project, for inland low country. However, work in the hills, such as around Culebra, was with pick, shovel, and mining cart.

After a small wave of fever hit the workforce in the spring of 1884, the excavation rate stopped accelerating and the stock took a hit on the Bourse, prompting an August communication from the corporate office (about to release a third bond issue) threatening sanctions if excavation rates did not improve.⁷⁰ When the issue was released that September, only 65% of the bonds were bought, and the fronting fees mounted to 8.4%.⁷¹ Then, within a couple of months, the fevers dramatically accelerated. In November of 1884 alone the hospitals reported 76 deaths from the fevers out of the population of some 1,200 European employees of the *Compagnie* who would have had access to the system. This began to severely impact the engineering ranks. The deaths among the, at this point, 17,000+ contractor employees, who did not have access to the hospital system but who as a population were likely less susceptible, again were not recorded. U. S. Army Medical Corps physicians would later estimate that for each death in the hospital, there were two to four among the ranks of the employees without access.⁷² Anecdotal testimony held that the Jamaican laborers were literally dying by the trainload. During this season, project director Jules Dingler lost his wife, son-in-law, and both daughters to yellow fever.⁷⁵ The headcount on the project, which had been over 19,000 in the previous month, began to fall off.

Progress rates began to recover when the fever death rate fell off in early 1885, only to be impacted again when fever returned with equal virulence during the 1885 rainy season. An April revolt in Panama by separatists was violently suppressed by Colombian troops, who in the process killed a number of the *Compagnie's* Jamaican laborers. This would seriously hamper labor recruitment. Further, project director Dingler, in depression after having lost his family, drove several subordinate managers to resign and resigned himself in August.⁷⁹ Detailed engineering problems, such as how best to handle the spoil not needed for diversions and dykes, were not getting solved. A U. S. Navy officer inspecting the work in late 1885 noted that only initial clearing had been done at site

††† The death index is the number of deaths per thousand employees on site from yellow fever and malaria normalized to the maximum number of employees ever on site (19,243 in October 1884).⁵⁵ The employment index tracks the fraction in place of the maximum number of employees.

§§§ This assumption was based on experience. On a 100 km railroad project in southern Mexico in 1862, one third of the West Indian laborers had died of yellow fever, as against two thirds of the European and North American engineers.⁶⁸

for the huge Gamboa dam and that calculations of the spillway dimensions needed to control floods were still being considered.⁷⁶ That June, when cumulative ACWP hit double BCWS, corporate officials announced at the shareholders meeting that the estimate-at-complete (EAC) of the project was to be raised to Fr 1.2 billion (the Congress' original estimate) and that the *Compagnie* was seeking government approval to issue lottery bonds in order to raise the funds, which would imply government backing of the project. The Suez project had applied the same financing mechanism but at a much higher percent complete than that the 11% at which Panama now stood. Even more, when the Suez Canal had become operational, the developing company had had a debt/equity ratio (not even accounting for a Fr 81 million government labor bailout) of 0.5. The *Compagnie* now had a debt/equity of 2.3. France's leading financial publication responded in August with its first negative appraisals of the prospects of the project (again assessing that traffic would not generate sufficient toll revenue for sufficient return on such a large amount of capital),⁷⁷ and in October the writings of the leading American critic of the effort (*New York World* reporter J. C. Rodrigues) were published in Europe as a book.⁷⁸ *Compagnie* stock saw its first serious declines on the Bourse.

The project office acted to turn things around. The new acting director, *Polytechnique* alumnus Phillippe Bunau-Varilla (27 years old at the time), increased efficiency by novating the many small contracts involved into five prime contracts, each responsible for construction along a specified length of the canal. Also, coming out of the 1885 rainy season, monthly excavation rates jumped to better 1,000,000 m³, 25% beyond any previous peak. This was due to a significant improvement in technology. It had been considered impossible for the steam ladder excavators to cut through rock. Thus, work in such ground had to be done manually. However, exhibiting a deep understanding of fracture mechanics and shock propagation, *Compagnie* engineers led by Bunau-Varilla developed a way to calculate patterns on which holes could be drilled by personnel standing on a raft floated above a rock formation and into which dynamite could be tamped. The resulting detonation would break the rock into sizes manageable by floating ladder dredges.⁸⁰ News of these actions reversed the course of the stock on the Bourse.

The positive effects lasted until May of 1886. At that point, the report of the French government's independent engineering audit of the project was made public. The government had commissioned the audit in support of its deliberations regarding the approval of lottery bonds. The report is generally full of praise for the project office and contractor teams, but, noting the disparity between ACWP and BCWP, makes a key statement: "Reconciliation of the estimate of expenses remaining to complete the canal with the funds which the *Compagnie* plans to obtain to cover them no longer allows hope that, barring major modifications to the approved design, such funds will be sufficient to take the project to completion on time."⁸¹ From the time of the Congress, the *Compagnie* had argued that the traffic model required a sea level canal, which in turn drove the selection of the Panama route despite the expense involved. A statement from this source questioning the possibility of such a canal even at the expense quoted brought the circularity of the *Compagnie's* argument into sharp relief. This shocked the investing public, sent the stock tumbling, and gave the up-and-out project office a significant challenge. Engineers at the project office and contractors began studies for a lock canal.⁸²

Surprisingly, the audit report belittles the impact that disease was having on the project. The mortality rate is noted as high, but no higher than that among naval personnel in any of France's tropical colonies. In fact, the auditor does not appear to see a connection between the mortality rate and the pace of progress and even claims that the disease rate was decreasing due to the measures being taken by the *Compagnie*.⁸³ Hospital statistics at this point do indicate a measureable decrease in fever death rate. However, the minutes of a conference between the project and corporate offices while the audit was underway reveal somewhat different thinking among the *Compagnie* management. The corporate office repeatedly chastises the medical service for not providing frequent statistics on health for both *Compagnie* and contractor personnel. The minutes also include a request by the medical service that glass windows be installed in certain hospital buildings, motivating an order by the corporate office that all *Compagnie* buildings were to be so furnished and revealing a continued belief (four years after the proposal of mosquito transmission in nearby Havana) that the fevers were spread aerobically. Further, the conference discussed measures to provide services to sick employees who chose to convalesce in their residences. This last point explains the improving death rate in the hospital system and, along with the later observations of U. S. Army physicians,⁷² indicates that employees had begun to understand, even if management did not, that the hospitals spread fever more than cured it. These conference discussions indicate that the management understood that the fevers were impacting progress, not so much by gutting the labor force as by decapitating the engineering force, hence their continued investment in a hospital system that served their direct employees. However, management was clearly continuing to

**** *Le rapprochement du chiffre des dépenses qui restent à faire pour achever le Canal et de celui des ressources que la Compagnie prévoit pour y subvenir ne permet pas non plus d'espérer qu'à moins de modifications profondes dans les projets approuvés, ces ressources soient suffisantes pour mener l'oeuvre à son terme."*

throw increasingly scarce resources at the wrong solution. It appears that they intended to prevail through the disease issue by “brute force” of numbers, as had the Panama Railroad project. Notably, Boyer, the sitting project director who took the glass widow action item from corporate management (and whose own recommendation to abandon the sea level canal design was submitted to the *Compagnie* simultaneously with the release of the government report⁸⁴), was, within two months of the meeting, dead of yellow fever.

The up-and-out corporate office did not respond well to the audit report. Rather than immediately conducting an open reappraisal of the design and perhaps building a convincing public story that a lock canal might profitably support traffic after all, the corporate Review Board simply held to their earlier recommendation for a sea level canal. The publicity mechanism continued to put out positive news and to project the high traffic that would support having such a canal. Allowing for the rainy season, the project office delivered steady, if not improving, excavation reports. The stock stabilized on the Bourse, and the *Compagnie* was able to raise another Fr 195 million on the bond market (at a fee of under 6% this time).⁸⁶ However, the continued exponential increase in costs above those of the 1883 plan motivated the *Compagnie* to formally open a study for a lock canal in January 1887. After a bond issue in July resulted in only just over half the bonds being sold (with a net fee back up near 7%), the corporate office’s Review Board called for designs for a “temporary” lock canal that, with continued dredging, could eventually be brought to sea level.⁸⁷

VII. The Delta-CDR and Final Collapse

With support of the project office, contractor engineers (now led by Bunau-Varilla, who had left the project office) brought forward a design in November 1887 wherein a series of five locks (~11 m lift each) would carry a ship to and from a summit water level of 49 m in the cut at Culebra.⁸⁸ A specialized subsystem contractor, noted for the then new steel fabrication technology and whose design staff had just completed work on a major demonstration project in the field, would be brought in to design and build the locks (See Fig. 6).^{†††} This new design would follow the route of the sea-level canal, and, as most of the diversion channels would still be needed for extreme floods, little work toward the previous design would be wasted. The summit waterline of this design was so high that there was some discussion that active pumping of river water might be needed to feed the canal during dry spells, but this was not without precedent.¹²⁴ Assuming stable cut walls at Culebra per Fig. 2c, the lock design was projected to require 34,000,000 m³ of excavation beyond the 42,476,605 m³ done as of that time, would cost an additional Fr 600 million from that point forward (bringing the canal total to Fr 1.6 billion), and would be operational by 30 June 1890.^{89,90} The Review Board and the *Compagnie* approved this “Delta-CDR” design in December 1887. Figures 5 b and c reflect the Delta-CDR’s planned excavation rates, BCWS, and BCWP starting from November 1887.

At this point, the *Compagnie* was desperate for cash, but no bill had yet been put before either house of the French legislature to finally allow the issue of lottery bonds. Thus, the corporate office arranged for legislators to be flooded with petitions for the bonds from shareholders asking for the signatures of the legislators themselves. In a later highly suspect legal maneuver, the signatures of legislators thus collected were declared to be equivalent to a majority vote for a law allowing the lottery bonds. The bonds were issued in March 1888, only 25% sold, and the resulting cash cost the *Compagnie* 14% in placement fees. The legislature later formally ratified the law allowing the issue. Work to the new design proceeded apace, with excavations during the first few months of 1888 being either on plan or above it. This allowed a short-lived recovery of the stock on the Bourse, but the positive technical progress reports were too little, too late. The final slide began in May. Another lottery bond issue in June sold 42% of the issue, but the stock continued to fall on the Bourse. When yet another bond issue was floated in December, the price of equity shares had fallen below that of the bonds, and the issue failed completely. *La Compagnie universelle du Canal interocéanique de Panama* went into receivership, and the receivers ordered all work in Panama to halt in May 1889 (by which time the number of employees on site had fallen to 835). The effort that started with the Congress of 1879 had utterly failed.⁹¹

VIII. Epilogue⁹²

Between shareholders and bondholders, the bankruptcy of the *Compagnie* had severely hurt some 800,000 French families (2.4% of the population as a whole). There were accusations that the corporate office had bribed legislators to win approval of the lottery bonds and had been wasteful of shareholders’ money during the effort. The resulting political fallout came to a head in 1893, with several executives of the *Compagnie* (including Ferdinand de Lesseps and, because of the high fees he charged for the lock project, Gustave Eiffel) being tried and convicted for

^{††††} The demonstration project was successful and has become known to Anglophones as the Eiffel Tower.

fraud. Due to appeals, none ever served time in prison except Charles de Lesseps (son of Ferdinand and Vice President of the *Compagnie*). A group of private investors was later formed as the *Compagnie Nouvelle*, with the object of maintaining the infrastructure in Panama and continuing, at a nominal rate, excavations with a goal of selling the assets and franchise to another entity. The Spanish-American War of 1898 renewed American strategic interest in a canal, and congressional committees began considering on appropriations to build such a canal along a route (seriously considered at the 1879 Congress) through Nicaragua. After a lobbying effort by the French (led by Phillippe Bunau-Varilla) that makes an exemplary case study for those in that profession and that even involved fomenting a revolution in Panama, the U. S. government shifted to the Panama route, and paid the *Compagnie Nouvelle* \$40 million (2008 \$22.5 billion) for their assets and franchise.

The U. S. government formed the Isthmian Canal Commission (ICC) as an independent agency (not unlike NASA) for the purposes of building and operating the canal. After again debating between sea-level and lock concepts, the majority of the ICC's independent board of engineers⁹³ actually recommended a sea-level design, while a minority recommended locks. After the debate was finally settled on the floor of the U. S. Senate, the ICC produced a design featuring a dam at Gatun (near the Atlantic coast) that formed a lake at 26 m above sea level to be reached by two parallel flights of locks (each 29 m wide; The canal channel would have a minimum waterline width of 60 m to make this a two-lane canal). Their excavation estimates assumed slopes for the Culebra cut walls similar to those assumed by the French Delta-CDR design (see Fig. 2d). In fact, as late as 1907, geologists on the project¹¹⁹ believed that the cut walls would be stable up to a slope of $3^{\text{vert}}:2^{\text{horiz}}$. The project was estimated (with margin!) to cost \$325 million (2008 \$151 billion), above and beyond the costs of the French assets and concessions.⁹⁴ Work began in earnest in 1907. One of the first things the ICC did was apply the techniques proven in Havana to, in a matter of months, eradicate yellow fever from the canal zone.⁹⁵ After scope increases including widening the canal to a minimum of 90 m at the waterline (three times that which the *Compagnie* had planned), the addition of fortifications, and a massive surprise in the slope required for the Culebra cut's walls (See Fig. 2e), the canal became operational in 1914 after 178,000,000 m³ of ICC excavation. Some 23,000,000 m³ of the *Compagnie* excavation were incorporated. The canal came in 7% under the 1907 budget. No engineers predicted the issues that would be experienced with the walls of the Culebra cut. It is obvious from Fig. 2e that a sea-level canal would never have been possible.

IX. Conclusion

The *Compagnie* utterly failed in their project for a ship canal in Panama. They did so due to two key mistakes on the part of the management of the program. Number One: Management failed to recognize the true attitude of their stakeholders (the French investing public), leading them to deliberately “low-ball” the cost the project. Number two: they failed to focus the scientific resources at their disposal to an plan attack on mosquito-borne disease. Both result from a fundamental mistake which any program management team could commit: emphasis on reactively deflecting threats to the project at the expense of recognizing opportunities to proactively get control of them. The only true engineering mistake made, that of baselining a sea-level canal, was not predicted by any critics at the Congress, and in fact the French never got far enough into construction to realize that such a design would have been impossible. The fact that they were motivated to correct the design by financial distress was in retrospect a rare stroke of luck in the effort.

The second mistake defined above resulted from project management's failure to recognize that the technical (i.e., medical) resources at their disposal could have been applied in both reactive and proactive modes. The chief technical criticism of their proposal to build the canal in Panama had nothing to do with their design and had everything to do with the workforce health risks associated with building *anything* in Panama. The massive investment made in medical facilities clearly indicates that project management reacted to this criticism and intended to show critics that they would try everything to deal with this problem. Given the pace of information flow at time, it is not surprising that their medical personnel did not happen on the alternative strategies. However, project management's mistake was in failing to direct these personnel to travel the fever-affected world and proactively seek alternative ideas. Such would have been well within their resources and consistent with the growing faith in the power of science at the time. An 1881 meeting between *Compagnie* physicians and colleagues in Havana could have contributed significantly to a better ending for this story.

Nevertheless, even correction of the second mistake could not have overcome the first. The decision to “low-ball” led to exponential cost overruns. The massive debt load which the project had to take on as a result of inadequate equity culminated by 1888 in the cost of capital alone making up a third of the ACWP per m³ (see Appendix II). This over-leveraged state at such a low percent complete is what ultimately inhibited the project from raising more funds. Project management's mistake appears even more staggering when one notes that the Suez IPO,

the start of the success that inspired the Panama project, had raised equity of Fr 200 million⁹⁶ when the EAC of the project was only Fr 162 million. Again, the management decision to “low-ball” resulted from their reaction to the attacks of critics on their business model. In assessing and reacting to these threats, management failed to see the opportunity presented by the beliefs of their actual stakeholders, revealed when they bid up the value of the Suez stock. The proactive step would have been to maintain the Congress estimate and float their IPO accordingly.

Some speculative calculations may be indulged at this final point (see Appendix III). If one assumes that the above mistakes had not been made, then the *Compagnie* would have raised Fr 600 million at their IPO and at worst might have controlled the fevers sufficiently to reach and maintain their monthly excavation record in Panama 1,337,000 m³ per month from June 1887 onward. One may also assume that the 34,000,000 m³ required to complete the Delta CDR design would have been increased by the 19,000,000 m³ in slides encountered by the U. S. ICC in the Culebra cut.¹⁰⁸ (This is conservative, as the French would have only gone down to a water elevation of 49 m, instead of the 26 m depth achieved by the ICC.) Even allowing for the increased carrying cost of the equity capital from the IPO, their debt/equity ratio would never have gone above 1.0, and they could have continued to place bonds. A canal would thus have become operational in July 1891 at a final cost of Fr 2.2 billion. This would represent completion of an operational canal two years earlier than projected at the 1879 Congress and at 83% over the Congress’ projected budget. Project management performance would thus have been better than that on the Suez Canal. Assessing whether this canal could have supported itself financially from tolls requires even more speculation. In its first full year of operation in 1914-5, the canal built by the U.S. ICC passed 5.4 million tons of shipping (averaging three ships per day).⁹⁷ At the Fr 15 per ton toll proposed by the syndicate at the Congress, this would have generated Fr 81 million in revenue, not equal to what would then have been the annual carrying cost of capital (Fr 100.6 million, see Table 2) and not at all covering an estimated¹¹⁸ Fr 18 million annual operating cost on top of that. However, the following year’s traffic of over 8 million tons (the 1879 Congress’ traffic model was perhaps not so overly optimistic) would have put them in the black.

Appendix I – Value Escalation

Escalation of money values over more than a century is patently uncertain. For this work the exchange rate between French Francs and US Dollars in the late 19th century is taken to be that used in Reference 8: Fr 4.6 per US\$. Subsequent escalation of US\$ values from the 1880’s to 2008 is done as a constant percentage of U.S. Gross Domestic Product (GDP) using the method and database defined in Ref. 98.

Appendix II – Earned Value Assumptions

The basic unit of earned value is taken as the cost of one m³ excavated from the canal axis and any diversion channels. Though some ancillary construction was done not involving excavation, such as the buildup Gamboa Dam, all elements of projected and actual cost are rolled into a rate of Fr per m³.

A. Actual Progress and Costs

All actual monthly excavation figures are taken from those reported in the various issues of Reference 99 during the period of *Compagnie* operations. As no figures were reported for the period September – December 1887, but no work stoppage is mentioned in any sources, excavation rates are estimated for those months based on performance during adjacent months. When including dredging volume in Colon harbor (as the *Compagnie* did), this correlates well with the totals recorded by the ICC’s review¹²⁰ of the French work. An ACWS is calculated for each fiscal year of operations post CDR, rolling in all of the costs for that year, including investment in fixed assets (which are assumed to have become worthless at the halt of work in 1889) and dividing by the excavation accomplished for that year. Actual cost figures and per unit ACWP for each year of operation are in Table 1.

Table 1. Project Cost Performance

	Project Total	Million Fr								
		FY 1880	FY 1881	FY 1882	FY 1883	FY 1884	FY 1885	FY 1886	FY 1887	FY 1888
		1881	1882	1883	1884	1885	1886	1887	1888	1889
Reference	100	101	102	a	103	104	105	106	b	b
Cost Element										
IPO/Concession Fees	10.9	10.9								
Stock issue fees	22.3	22.3								
Bond issue fees	83.1			7.3	9.9	7.8	2.1	11.5	31.2	13.2
Interest and Dividends	261.6	4.8	7.2	15.8	21.7	24.3	35.5	55.2	71.7	25.2
Corporate G&A - Paris	15.6	1.2	1.3	2.4	1.6	1.7	2.2	2.0	2.1	1.3
Direct Work - Panama	664.3	1.2	9.8	24.2	42.3	88.1	78.1	121.0	218.6	81.1
Total Expenses	1057.8	40.4	18.3	49.7	75.4	121.9	117.9	189.8	323.6	120.8
Net fixed assets - Paris	2.0	1.2	0.3	0.2	0.3					
Net fixed assets - Panama	117.8	1.1	10.1	25.0	37.5	20.5	26.5	14.6	-17.5	
Total Sunk Cost	1177.6	42.8	28.7	74.9	113.2	142.4	144.4	204.4	306.1	120.8
Book value - Panama RR stock	93.3									
Liquid Assets at Project End	163.7									
TOTAL	1434.6									
Annual Exc (Mm ³)	54.8	0.0	0.2	1.0	5.5	7.7	10.5	12.4	13.7	3.9
ACWP (Fr/m ³)		n/a	n/a	n/a	20.50	18.45	13.74	16.46	22.41	31.15

^aNo annual report is extant for FY 1882-3. Cost elements are calculated from data in reports of adjacent years and from element tables in Ref. 109.

^bNo annual report is extant for FY1887-8 or FY1888-9. Direct Work – Panama cost elements are estimated from extrapolation of per unit costs in previous fiscal years. Other cost elements are calculated from element tables in Ref. 109 and prorated to complete total cost reflected in Ref. 100.

B. Budget Costs and Scheduled Progress

Budgeted costs are taken as the total costs projected, respectively, from CDR in June 1883 and from Delta CDR in November 1887. As no copies of the *Compagnie's* excavation schedules are extant, the scheduled excavation progress for post-CDR is estimated to be an accelerating monthly excavation rate, with a 20% decrease assumed for

the June through November rainy season, and totaling to the projected required volume of excavation as of CDR. The scheduled excavation progress for post-Delta-CDR is taken to be a bilevel monthly excavation rate, with a 20% decrease assumed for the rainy season and totaling to the projected remaining volume as of Delta-CDR.

Appendix III – Speculative Calculations

Table 2 below details an estimated cost run-out for completion of an operational lock canal starting with an IPO of Fr 600 million. The percentage placement fees for the stock and stock dividend rate (5%) are assumed to be the same as in Table 1. Bond fees are assumed at 7% for placement and 4% for interest. The ACWP per m³ is assumed as in Table 1 through end of FY 1886-7. For subsequent years the ACWP of FY 1887-8 (unburdened by finance or G&A rates) of 29.91 Fr/m³ is assumed constant for the duration, as the additional cost of lock gates, masonry, and other equipment are already wrapped into the excavation rate for that year.

The excavation-to-complete is assumed to be that projected by the *Compagnie* for a lock canal with a summit waterline elevation of 49 m with the addition of the volume of slides encountered by the U. S. ICC (for a much deeper canal), for a total from the end of FY 1886-7 of 57.5 Mm³. Excavation rate is assumed to be held constant at just below the record monthly rate for the *Compagnie* in Panama (1.3 Mm³) so as to achieve completion 4 years after the end of FY 1886-7.

Table 2. Speculative Cost for Operational Lock Canal

Cost Element	Million Fr					
	Est Total	Est 1880 1887	Est 1887 1888	Est 1888 1889	Est 1889 1890	Est 1890 1891
IPO/Concession Fees	10.9	10.9				
Stock issue fees	44.6	44.6				
Bond issue fees	117.2	27.4	12.3	21.1	27.4	29.0
Interest and Dividends	531.3	221.7	56.4	68.4	84.1	100.7
Corporate G&A - Paris	20.6	12.2	2.1	2.1	2.1	2.1
Direct Work - Panama	1252.3	121.0	229.9	300.4	300.4	300.4
Total Expenses	1977.0	437.9	300.7	392.0	414.1	432.2
Net fixed assets - Paris	2.0	2.0				
Net fixed assets - Panama	117.8	117.8				
Total Sunk Cost	2096.8	557.7	300.7	392.0	414.1	432.2
Book value - Panama RR stock	93.3					
Liquid Assets at Project End	0.0					
TOTAL	2190.0					

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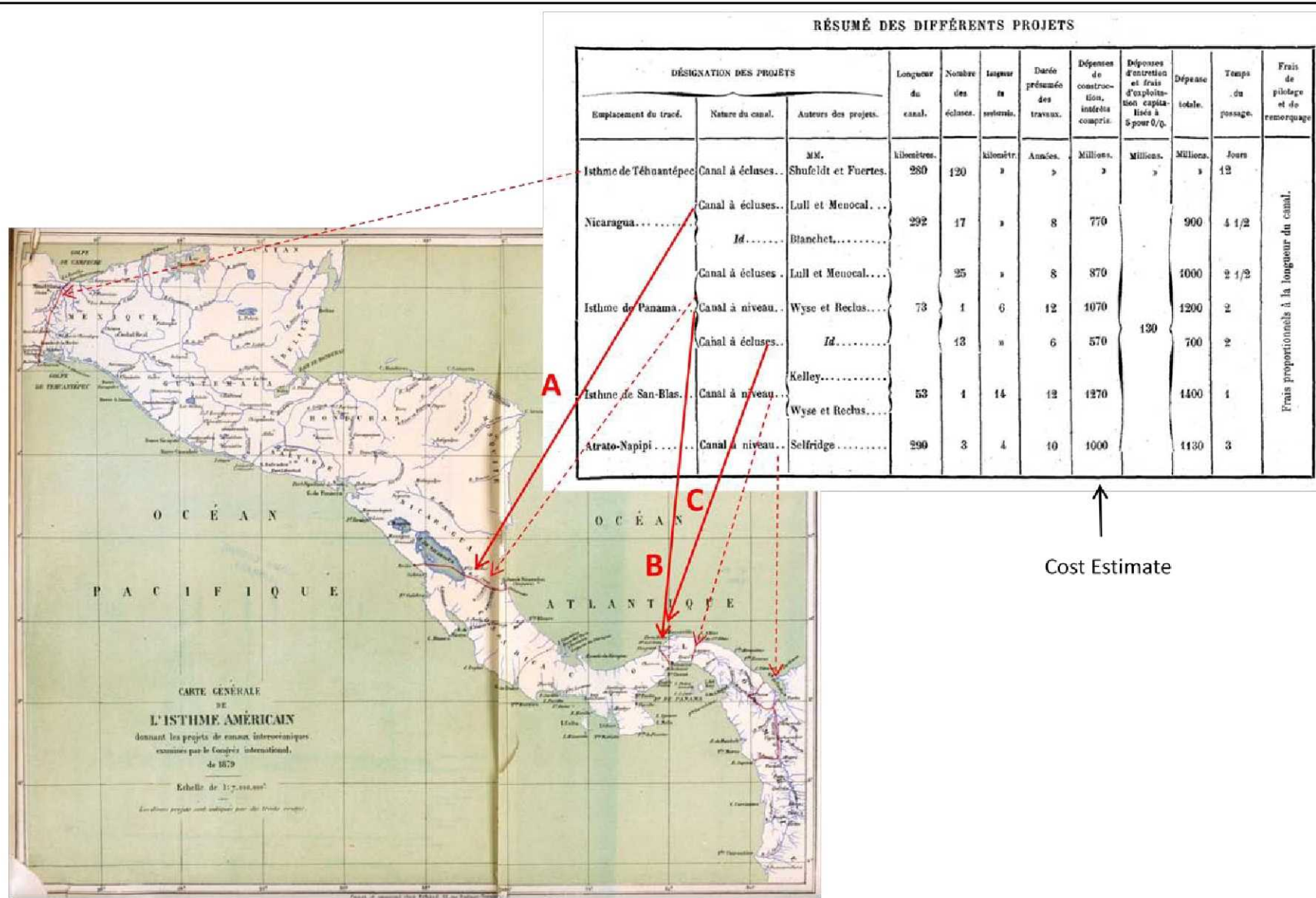
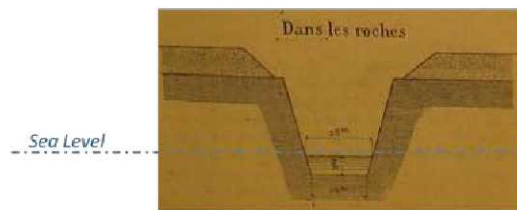
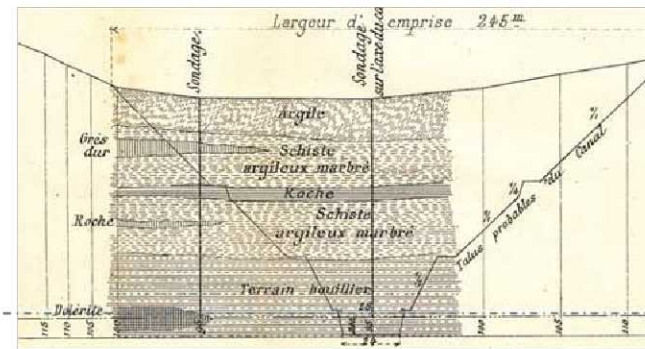


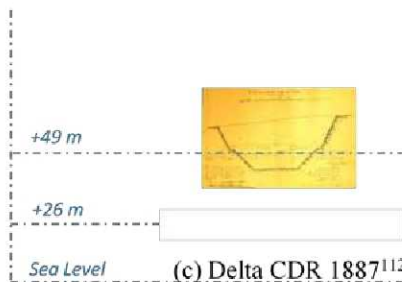
Figure 1. Trade Space from *Congrès International*^{25,26}



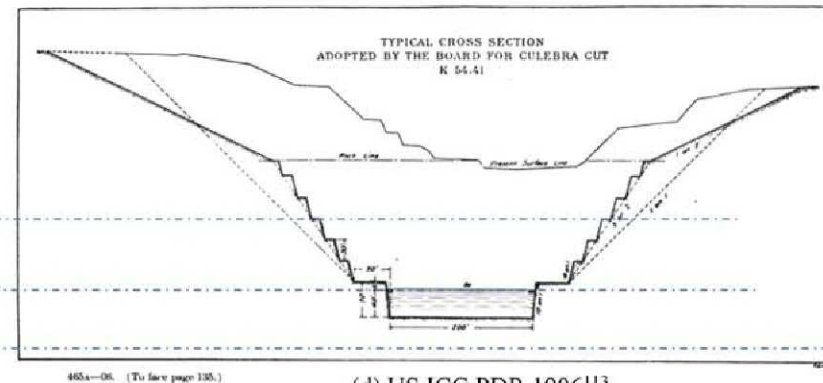
(a) PDR 1880¹⁰⁹



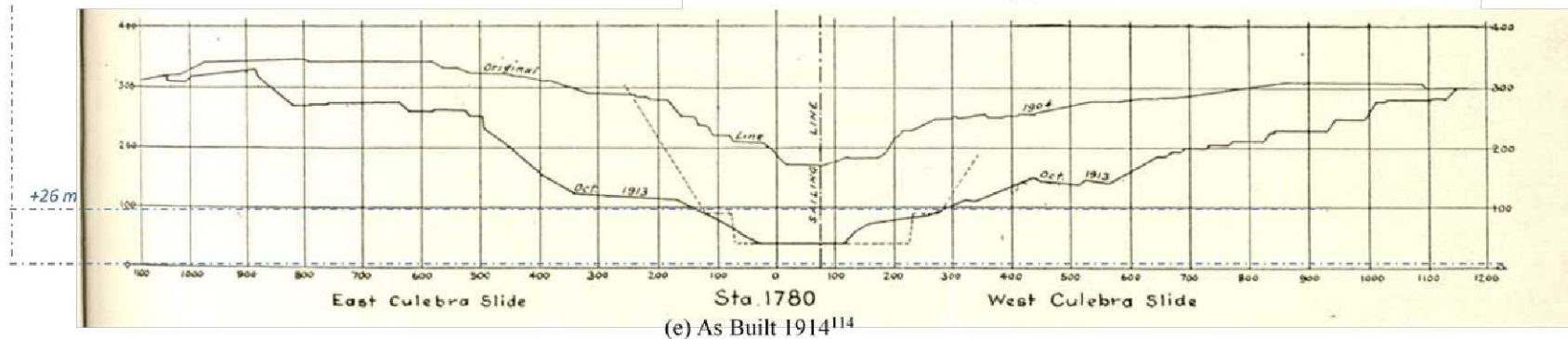
(b) CDR 1883¹¹⁰



(c) Delta CDR 1887¹¹²

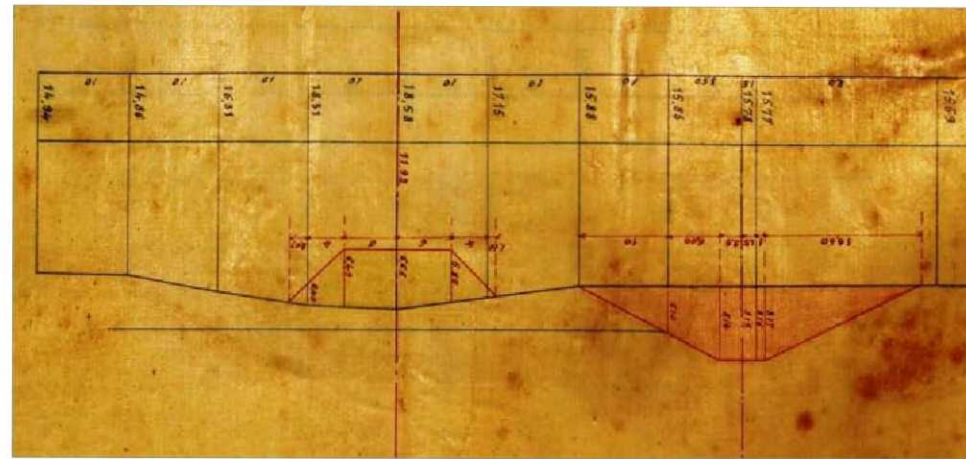


(d) US ICC PDR 1906¹¹³

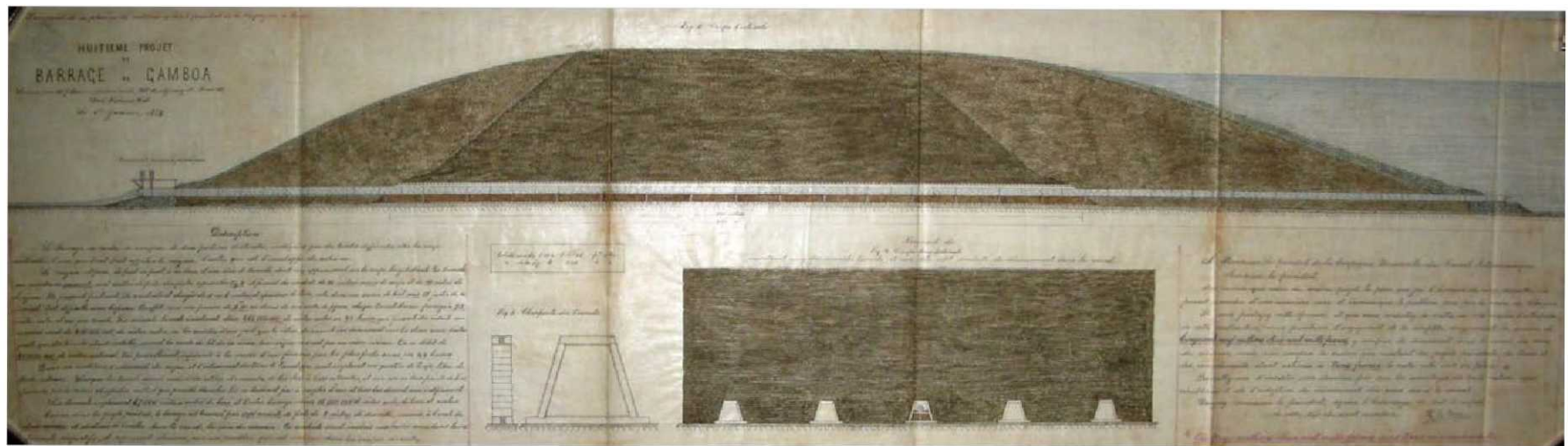


(e) As Built 1914¹¹⁴

Figure 2. Evolution of the Culebra Cut (to approximate scale)



(a) CDR River Diversions¹¹⁷



(a) CDR Gamboa Dam¹¹⁶

Figure 4. CDR Diversion and Dam Designs

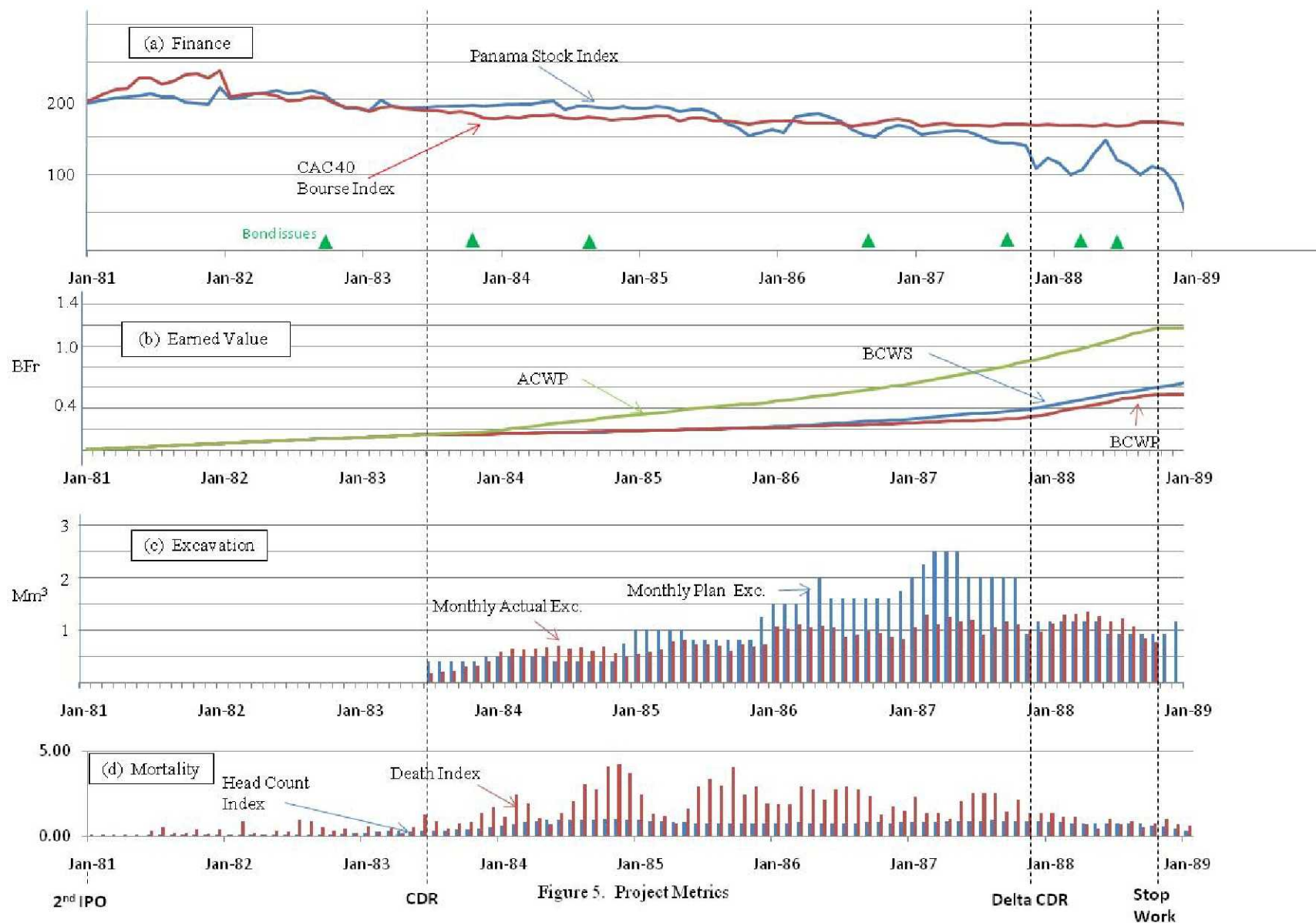
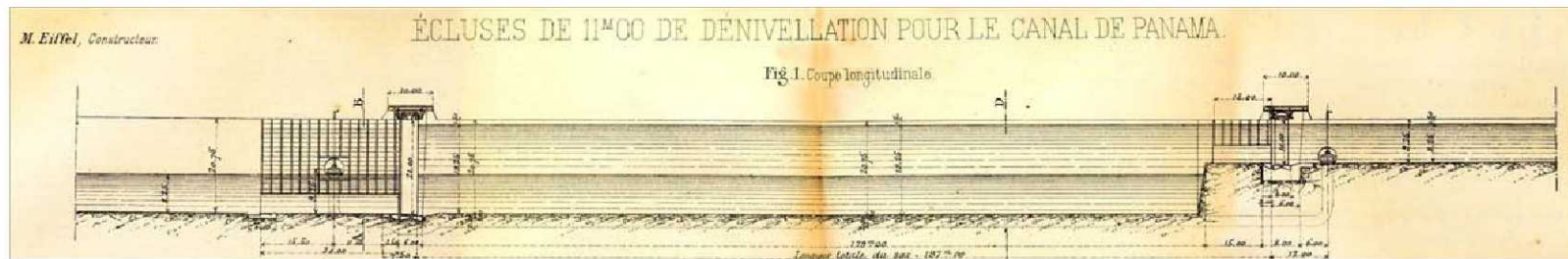
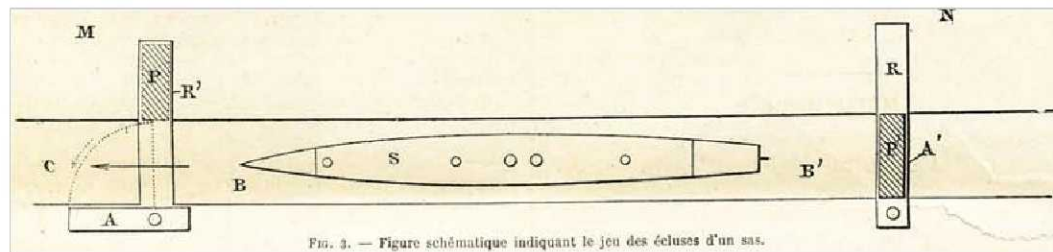
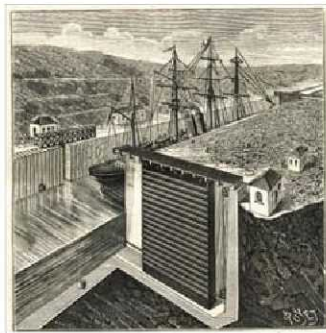


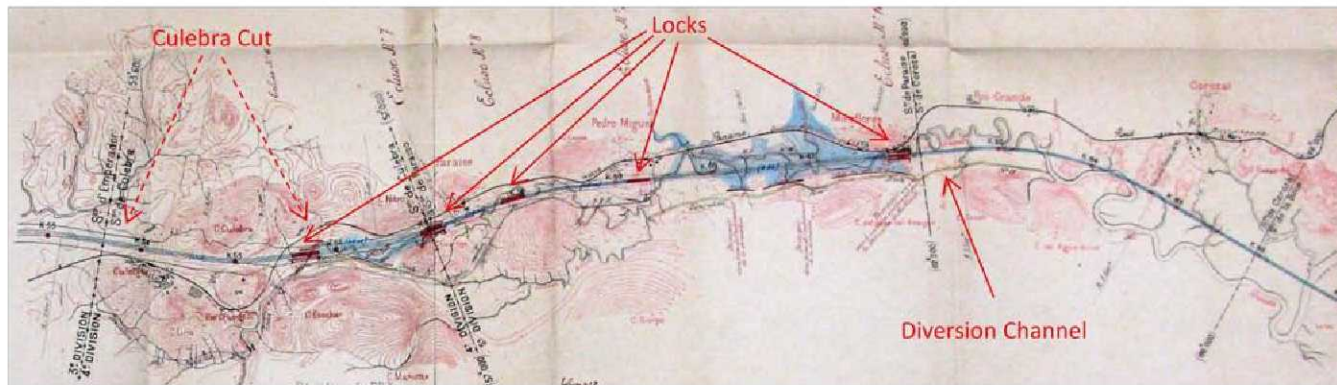
Figure 5. Project Metrics



(c) Section View¹²³



(b) Operating schematics¹²²



(a) Plan View – Pacific Slope¹²¹

Figure 6. Delta CDR Lock Canal