SITE CONDITIONS FOR PORT DEVELOPMENT IN CENTRAL PANAMA'S ATLANTIC COAST

by

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ABSTRACT

The purpose of this paper is to present a general description of the geological and seismic conditions in the Atlantic coast in the vicinity of the of the Panama Canal. Geologic conditions involve very soft marine sediments, as well as a predominant rock formation that presents distinctive characteristics. Seismic conditions were revised in 2016, based on studies made in support of the Panama Canal Expansion Program. This paper describes proven best practices and analyzes the potential impact of the stronger ground motions on such practices.

1. INTRODUCTION

The construction of the Panama Canal has motivated the development of multiple ports at both ends of the 80-km long Canal. With the expansion of the Canal, and its new NeoPanamax-size locks, it is likely that additional port facilities will be built in the near future. Container Traffic in 2016 on the Atlantic coast of central Panama reached 3.2 MTEU (million twenty-foot equivalent units) (2). CAF Banco de Desarrollo de America Latina estimates that this traffic will grow to 13.5 MTEU by 2040 (2). Such forecasts imply the need for a significant increase in port facilities in the area. Figure 1 presents a map of the Atlantic Coast of central Panama (Canal area), with existing ports and other facilities.

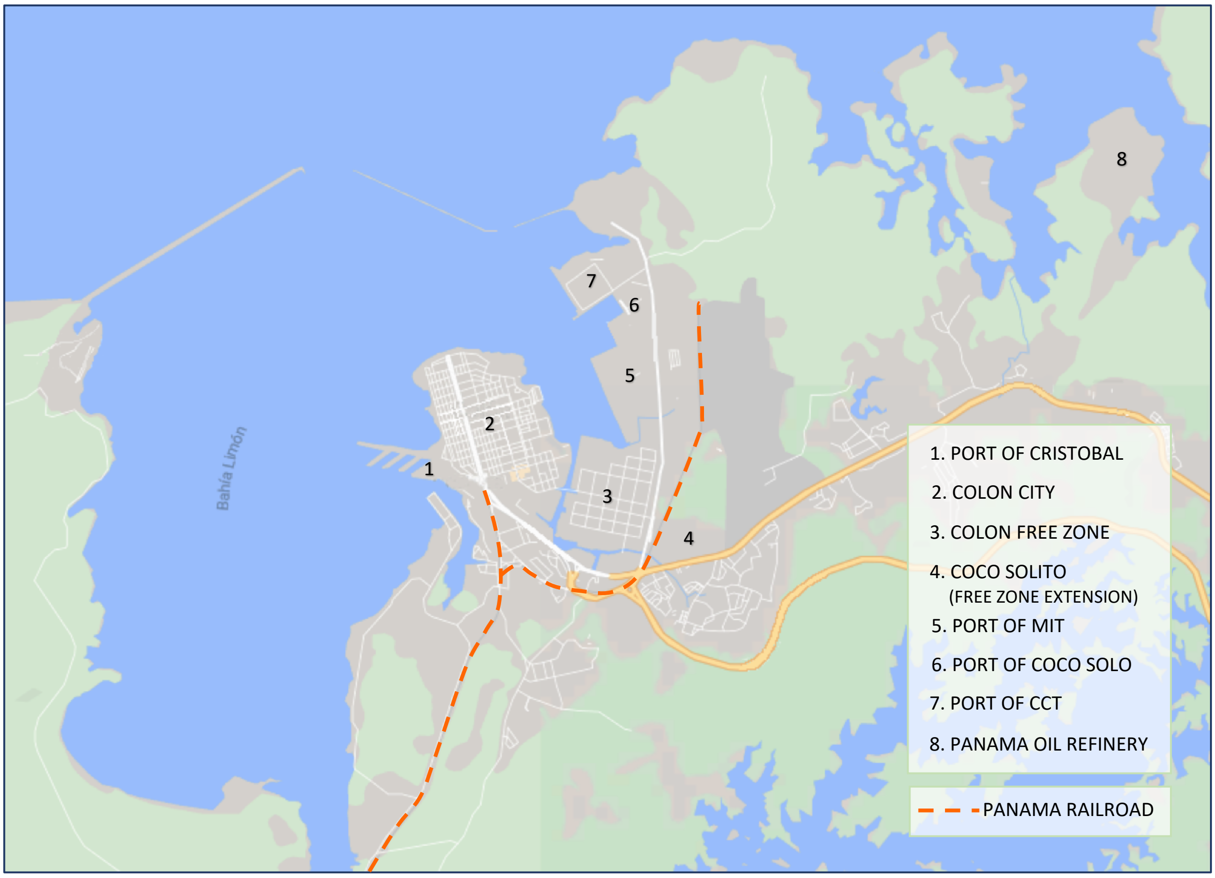

Figure 1: Area of interest with main facilities

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2. GEOLOGIC CONDITIONS

Figure 2 presents and extract of the Geologic Map of the Panama Canal and Surrounding Areas prepared by Stewart et al (15) for the Atlantic region. Three dominant geologic formations are of interest: The Gatun Formation (Tg), The Undivided Holocene sediments (Qa), and the Holocene fringing coral reefs (Qr). Appendix A presents a legend and a correlation diagram that indicates the placement of these formations in the geologic history of the area. Following is a brief characterization of the three formations identified.

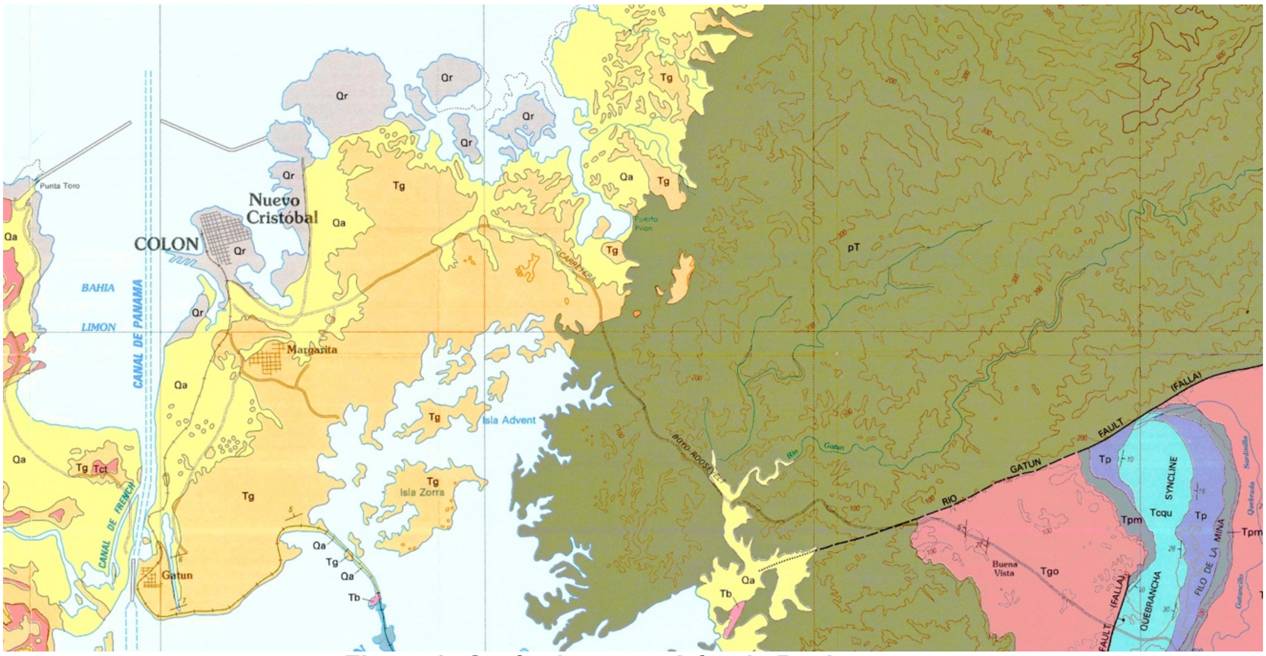


Figure 2: Geologic map – Atlantic Region

2.1 Gatun Formation (Tg).

This is a middle Miocene sedimentary formation composed of sandstones, siltstones, tuffs and conglomerates.

Jones (8) describes the Gatun as "mudstones, siltstones, conglomerates and tuffs, all thickly and massively bedded. The siltstones, sandstones, and conglomerates are variably marly and tuffaceous, highly fossiliferous and massively jointed... The tuffs are uniformly grained siltstones and claystones except for local streaks, sparsely scattered with pumice pebbles and cobbles. The formation has a thickness known to exceed 1,400 feet and probably much more. The beds dip north-westerly to northerly at angles ranging uniformly from 2º near the shore of Limon Bay to as much as 20º in a few places near their south-eastern border. The depth of overburden and weathered rock averages about 30 feet on this formation. The weathered rock is soft and grades imperceptibly into red clay soil." Appendix 1 in this reference, provides a detailed description of the sequence of the lithologic units contained in this formation.

De Puy (7) presents a summary of material parameters for the Gatun Formation, based on extensive testing performed by the Autoridad del Canal de Panama in their geotechnical laboratory. Table 1 presents various statistics that provide a sense of the range of values for these material's parameters. These statistics incorporate the various lithological groups contained in the formation, without any segregation. These groups include the following rock types: sandstone, sandstone fossiliferous, sandstone conglomeratic, sandstone pumiceous, siltstone, tuff, and conglomerate.

De Puy (7) also reports geophysical tests which reveal that the shear wave velocity ranged between 400m/s to 900m/s for sound rock, and between 300m/s and 600m/s for weathered rock. Triaxial testing of intact samples revealed an average internal angle of friction of 56º, and an average cohesion of 3.3 MPa.

Table 1: Parameters for materials of the Gatunn Formation

Parameter	Number of tests	Mean	Mode	Standard deviation	Coefficient of Variation	Minimum value	Maximum value
Unit weight (kg/m^3)	466	1,859	1,900	179	9.6%	1,313	2,435
Unconfined compressive strength (MPa)	532	5.5	4.0	3.7	67.3%	0.6	42.4
Elastic Modulus (MPa)	466	1,228	800	786	64.0%	149	6,462

2.2 Undivided Holocene Sediments (Qa).

This is a Quaternary formation composed of marine and fluvial sediments. Stewart et al. (15) included man-made fills in this formation. This formation is commonly referred to as Atlantic Muck in technical documents and in general practice.

A general characteristic of this formation is that it is very heterogeneous. Mesa (12), through a systematic program of laboratory tests, provides ranges of material parameters measured for marine sediments in central Panama. Table 2 summarizes these parameters for the Atlantic Muck.

Table 2: Parameters of the Atlantic Muck

Parameter	Low value	High value
Natural water content – w(%)	43	138
Liquid Limit - LL	45	83
Plasticity Index (PI)	17	35
Specific gravity of solids (Gs)	2.46	2.79
Moist unit weight – γ_m (T/m3)	1.44	1.84
Dry unit weight – γ_d (T/m3)	0.73	1.28
Preconsolidation pressure – p'_c (kg/cm^2)	0.22	0.80
Coefficient of consolidation – c_v (cm^2/s)	0.11 x 10^{-4}	20.9 x 10^{-4}
Oedometric modulus – mv (cm^2/kg)	0.001	0.202
Compression index – Cc	0.20	1.71
Vertical Coefficient of Permeability – k_v (cm/s)	0.1 x 10^{-9}	1.97 x 10^{-7}
Horizontal Coefficient of Permeability – k_h (cm/s)	9.9 x 10^{-8}	1.25 x 10^{-7}
Cohesion – c (T/m2)	0.2	1.95
Angle of internal friction – ϕ (degrees)	2	13
pH	6.8	7.0

2.3 Holocene fringing coral reefs (Qr).

Kennedy et al. (10) state in their abstract: “Fringing reefs are generally not simple veneers of coral growth along tropical shorelines. Extensive research over the past few decades, based on radiocarbon dating of Holocene reef deposits, has indicated that they can develop in a complex variety of ways even though the surface morphology may appear relatively simple. The principal factor that appears to determine the growth and morphology of fringing reefs is the available accommodation space. Sea-level fluctuations are important, primarily because the sea surface determines the absolute accommodation space for a given reef. This means that a reef established during a period of sea-level rise will be able to accrete vertically as space is created above it. If, however, the reef establishes at, or grows to, the sea surface, thereby occupying all the available accommodation space, it can no longer accrete vertically and begins to build laterally."

This formation has not figured prominently in projects developed in the area, except in two instances: (a) dredged coral reefs are stored by Canal authorities and used as competent fill material when required; and (b) driving concrete piles through these materials may require pre-drilling. Apart from these comments, this formation will not be addressed further in this paper.

3. SEISMIC CONDITIONS

Central Panama has been subjected to two important earthquakes. Figure 3 shows a map (6) indicating the estimated location of the earthquake of 7 September 1882. Intensities are in the Modified Mercalli scale.

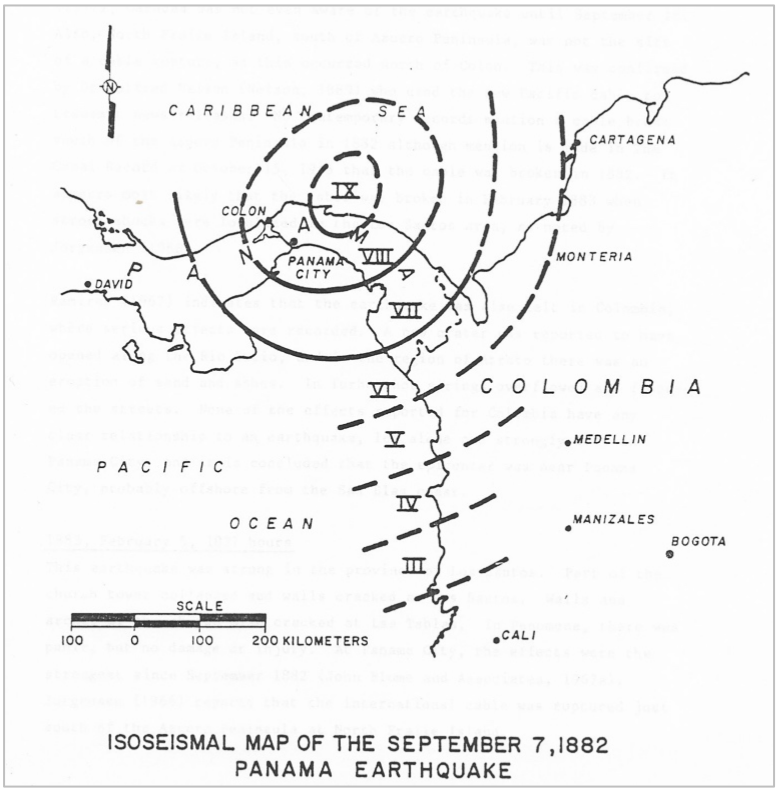


Figure 3: Estimated location of Epicenter – 1882 Earthquake

It originated on a subduction zone called the North Panama Deformed Belt, which is shown in Figure 4 (19).

Figure 5 shows an extract of the Geologic Map of the Panama Canal and Surrounding Areas prepared by Stewart et al (15) for the Pacific region. Crustal Fault Pedro Miguel, shown on this map, is believed to be source of the 2 May 1621 earthquake.

Historical accounts of these earthquakes (4, 5, 6, 11, 13, 20) led the *Autoridad de Canal de Panamá* to perform a detailed characterization of the seismicity of the region. This information was used for the design of the new Pospanamax locks and the new earth dams required for the Canal Expansion Program. Association of the Pedro Miguel Fault and the 2 May 1621 earthquake is presented in (14).

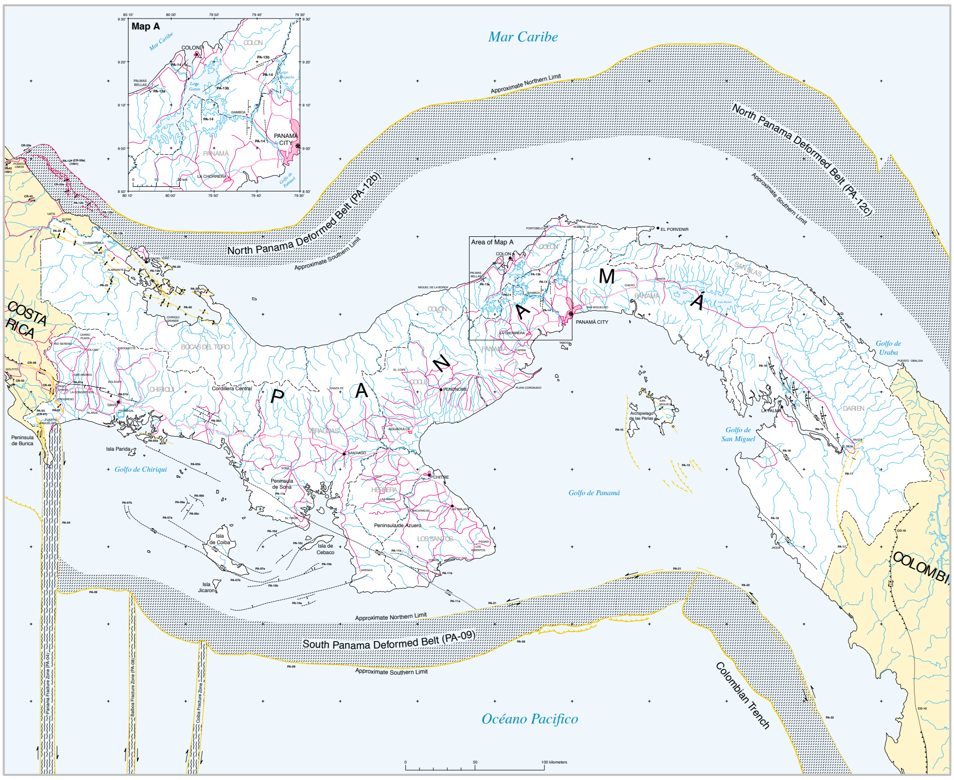


Figure 4: USGS map of faults and folds - Panama

Later, the information was transmitted to the *Junta Técnica de Ingeniería y Arquitectura*, institution that regulates the practice of engineering and architecture in the country, and created and maintains the Panamanian Structural Design Code, or REP which is its acronym in Spanish (9). The new ground motion assessments were incorporated in the 2014 version of the REP, which was published in 2015 and enforced in 2016.

Figures 6 present s a map with peak ground accelerations, from a Probabilistic Seismic Hazard Analysis, for a recurrence period of 2,500 years (16, 17). We note that in addition to the higher ground motions, the code also incorporates the use of a recurrence interval of 2,500 years, instead of the 475-year recurrence interval used by previous versions of the codes. The new ground motions also increase the seismic design category for structures in many areas.

The increase in ground motions identified by the new code, has a direct impact on ground response, structural response, and associated phenomena such as liquefaction. These issues must now be given greater attention.

This map reflects the influence of the North Panama Deformed Belt, and of the crustal faults, believed to be active in the area (14). These are the Pedro Miguel Fault (shown in Figure 5), the Gatun Fault (shown in Figure 2) and the Limón Fault (not shown but believed to be a possible extension of the Pedro Miguel Fault to the North).

This map provides an integral conception of the seismicity of the area. It was later complemented by a Deterministic Seismic Hazard Analysis, which was used to “cap” the probabilistic analysis near the three crustal faults mentioned. The resulting maps for peak ground accelerations, spectral accelerations for 0.2 s, and spectral accelerations for 1.0 s are included in (9). These are the maps that should be used for design.

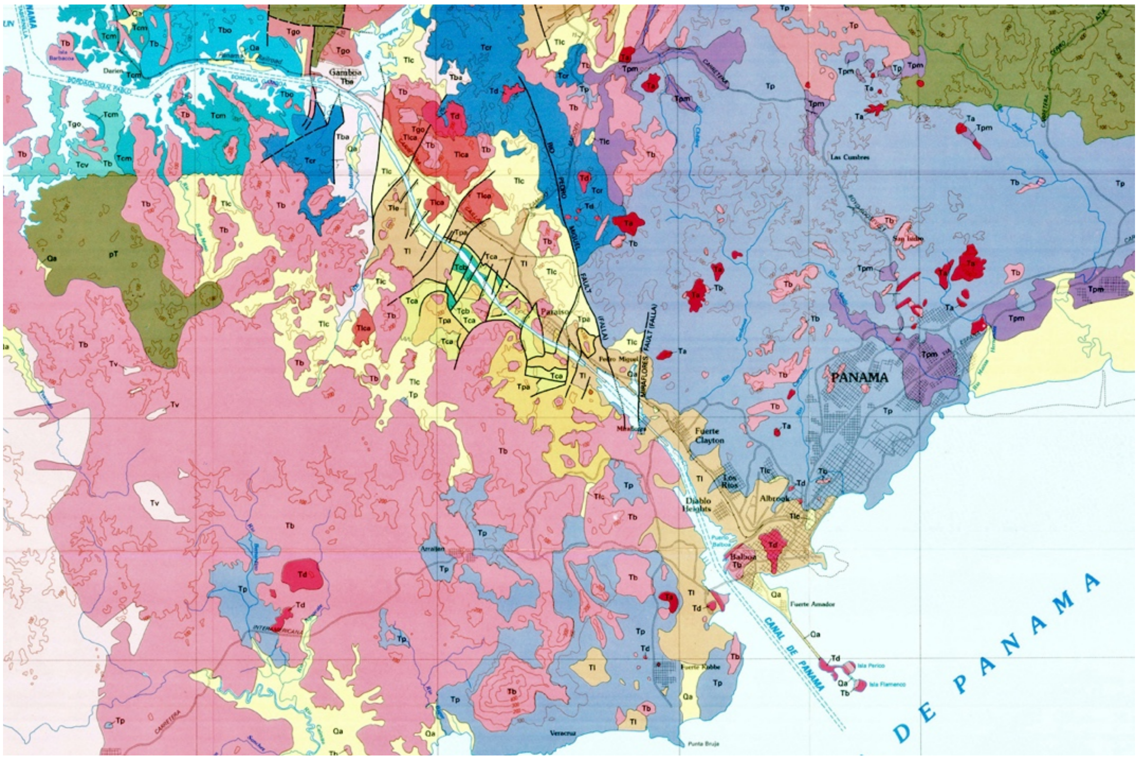


Figure 5: Geologic map – Pacific Region

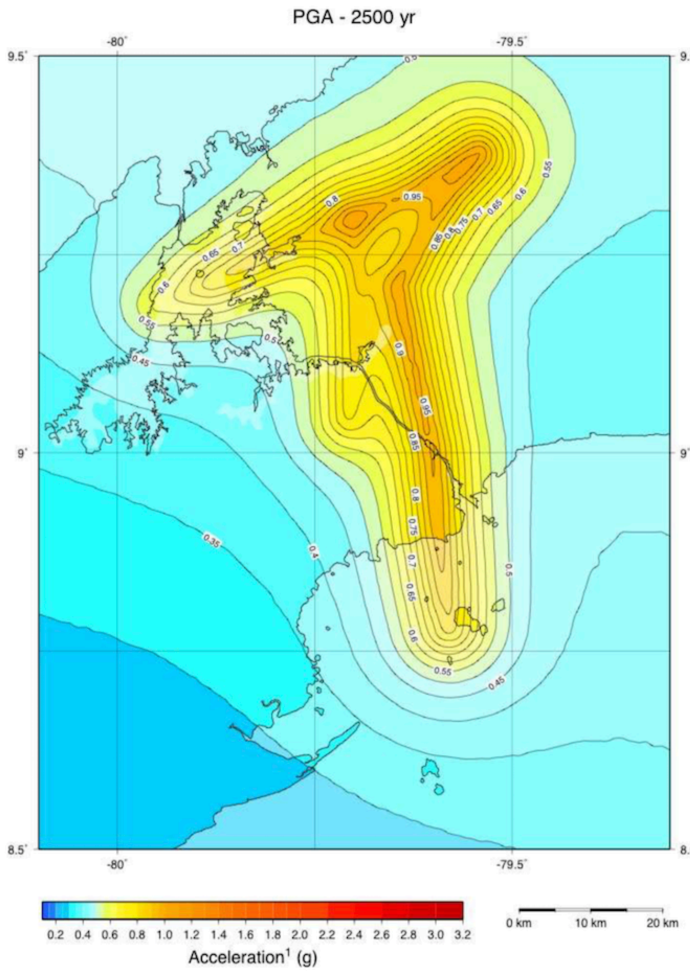


Figure 6: Peak ground accelerations 2,500 return period – Canal area

4. EXPERIENCE WITH THE GATUN FORMATION (Tg)

For over a century, large civil works have been developed on the Atlantic area, as shown in Figure 1. This has required an understanding of the characteristics of the Gatun Formation (Tg) and the Undivided Holocene Sediments (Qa). Engineering practices for dealing with these materials have progressively evolved with each major project. This experience provides a wealth of information that is beneficial to the development of future projects. Following are the principal learnings with various types of situations and problems.

4.1 Excavation process in the Gatun Formation

The Gatun formation does not present a significant amount of weakness planes that control its behavior, as is common in many other geologic formations in the region, which are of volcanic origin. Therefore, relatively steep slopes can be excavated without much risk of instabilities. The first excavations performed for the Third Set of Locks in the Panama Canal, began in 1940, but were stopped in 1942 due to World War II. The excavations were left in place since then. Of the almost 5 km of slopes left in place (including both banks of the 2,400m channel), only a minor wedge-type slide took place in the stated period. When the Third set of Locks project was restarted on the Atlantic side in 2009, excavations continued, as the new locks are much larger than those envisioned in the 1940s) from where they were left in 1942. Again, no significant instabilities took place.

With modern excavation equipment, excavating sound Gatun Formation usually does not require the use of explosives. The latest deepening of the Atlantic Entrance of the Panama Canal was performed with a large cutter-suction dredge, without prior blasting.

The same has been observed with dry excavation on land. Explosives are not necessary and are only used when a higher productivity is warranted. It becomes a matter of economics: time and cost of excavation with explosives versus time and cost of excavation without explosives.

In general, excavation in the Gatun Formation is a relatively simple process, with none of the ubiquitous landslide problems present in the Canal's Gaillard Cut, where the Canal crosses the continental divide in the isthmus.

4.2 Foundations on the Gatun Formation

The material parameters presented in Table 1 indicate that this material can be considered a soft rock. Shallow foundations on rock outcrops can usually be designed for an allowable bearing capacity of 2,000 kPa.

Drilled pile foundations can be designed for a similar tip resistance if the pile has little penetration into sound rock. A pile socket into bedrock would require a more detailed analysis to establish consistent tip resistance and shaft friction resistance in the socket. Drilling into the Gatun formation poses no difficulties for pile drilling equipment.

Driving piles into the Gatun formation is another matter. Even with hardened steel tips, it is difficult to drive concrete piles or steel piles (pipes or HP sections) into the Gatun Formation. Concrete piles do not penetrate into the Gatun formation. Excessive driving will damage them. Similarly, steel piles will suffer buckling and rupture before penetrating into sound Gatun. If driving piles into sound Gatun is required to achieve a condition of fixity, pre-drilling is necessary. The use of test piles is very convenient for a large project, to determine realistic construction needs before beginning production pile driving.

The higher ground motions in REP-2014 favor the use of more flexibles structures, so the use of batter piles is, in general terms, undesirable.

4.3 Using Gatun Formation materials as fill

Materials of the Gatun formation have been used extensively for constructing fills in many of the projects shown in Figure 1. This includes the city of Colon, the Colon Free Zone, the Oil Refinery, all of the ports, the railroad and various highways.

Fills constructed with materials from the Gatun Formation are excellent, if proven practices for construction, as outlined below, are followed.

- The material should be used as soon as it is extracted from the borrow area. This limits exposure time that promotes weathering. The clay content of these materials deteriorates when in contact with air and water. The excavated materials from the Gatun Formation should not be stored temporarily in stockpiles. Cutting from the source and filling at the project site should be a continuous operation.

- The equipment used to excavate the material should be such that, the largest block size is 40 cm.
- The fill must be placed in layers that are 30 cm thick. It has been observed that material with a largest block size of 40 cm will result in a layer of 30 cm when compacted.
- The fills must be compacted using optimal water content, achieving a dry density of 98% of the maximum given by Standard Proctor test. The degree of compaction must be verified in the field based on requirements defined by the Ministry of Public Works (MOP).
- At all times during fill placements, the top surface of the fill must have a slope greater or equal to 2% to avoid the infiltration of runoff during and after periods of precipitation.
- If the surface on which the fill is to be placed is soft, a woven geotextile, performing a separation function, must be placed at the site before filling commences. Afterwards, the fill can progress as indicated above. In no case can a layer of boulders be placed over the soft soil, with the supposed intent of "stabilizing the area" before fill construction.

Large shear box testing of crushed Gatun formation samples (7) revealed an average internal angle of friction of 33º and an average cohesion of 0.025 MPa. De Puy.

Berman et al. (3) present a project in which materials from the Gatun formation were used to construct a fill, utilizing the procedure outlined above. The resulting compacted fill exhibited Standard Penetration Test results with an average of N = 33 blows/foot. A mat foundation 8.0 meters wide was selected by the client to support a series of low-rise buildings, and a Plaxis 2D model was used to estimate potential settlement under a uniform load of 50 kPa. The prediction was that settlements would be limited to 10.0 mm. Actual performance of the structures has been excellent. Measured settlements have not exceeded 7.0 mm.

5. EXPERIENCE WITH THE UNDIVIDED HOLOCENE SEDIMENTS (Qa)

5.1 Consolidation of the Sediments

The material parameters shown in Table 2 evidence the high compressibility of these sediments. Compression indexes as high as Cc = 1.71 are indicative of very large void ratios and very significant potential settlements under load.

Light structures built on these materials, or on several meters of fill placed over these materials, have exhibited significant damage, and in some cases collapse, when a site is not prepared (stabilized) properly.

5.2 Liquefaction potential in the Sediments

The 1882 earthquake caused extensive liquefaction in zones of predominantly sandy materials. Figure 7 presented in (4) shows the general area (hatched) where liquefaction was reported. The figure also shows the areas affected by Tsunami, which was the main cause of death during the earthquake.

It is interesting that the term liquefaction was not yet in use at that time. Camacho and Viquez (4) quote The Star and Herald, the local newspaper of the day, stating (translated to English): "In Donoso (a town) on the coast of Colon…craters were observed from which gushes of water were ejected, reaching almost the height of a house. In (another location) close to this town, a 10-meter wide crack opened in the ground."

In 1991, the Limon M7.6 earthquake in Costa Rica (also generated on the North Panama Deformed Belt) caused extensive liquefaction in similar coastal sediments along the Atlantic coast of the province of Bocas del Toro, the westernmost part of the Panamanian Atlantic coast.

The higher ground motions in REP-2014 increase the importance of performing appropriate liquefaction triggering evaluations for sites in which the materials may be susceptible to this phenomenon.

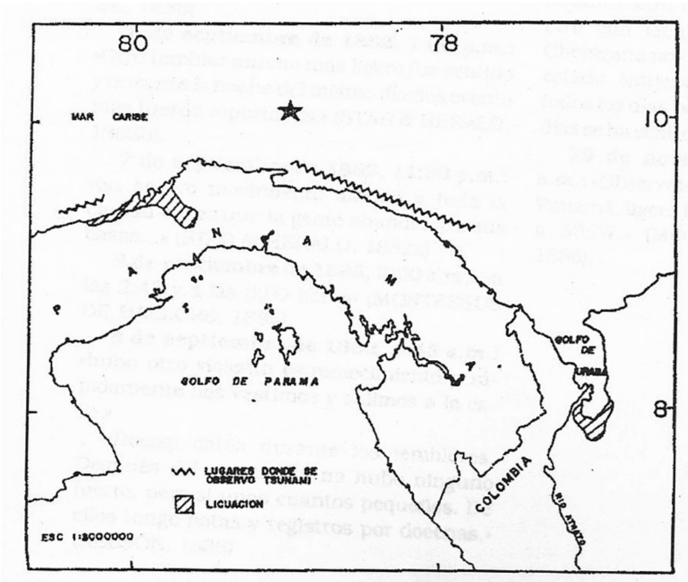


Figure 7: Areas of Liquefaction and Tsunami – 1882 Earthquake

5.3 Construction on Sites with Soft Sediments

Container yards, roads, dredge disposal sites and light structures have been built in areas that present soft sediments in their geologic profile. All can be safely built with the proper site preparation. The opposite is also true. In some cases, structures are supported on piles, but the ground slab is supported on grade. The differential settlements generally cause damages to the affected structures.

Preloading has worked well in the past to increase the strength and reduce the compressibility of these materials. The use of vertical wick drains, piezometers and settlement plates make it very straightforward to prepare a site for its reliable use.

Furthermore, experience has shown that consolidation under preloading is relatively quick. Often 6 to 12 months will suffice to make a site adequate if vertical drains are not used. If they are used, it would take significantly less time. Plotting the performance of settlement plates, and the reduction of excess pore pressures in piezometers, make the process very reliable. The end of consolidation is readily detected, and the site can perform well under loads that are lower or equal to the preloading applied.

Alfaro et. al (1) describe the difficulties that these sediments posed for the construction of the Gatun Dam in the early XX Century. This is a key structure of the Panama Canal, as it impounds the Gatun lake to enable the use of the Canal´s locks. A model dam was constructed to validate solutions to these very adverse conditions. The success of the dam is indicative that construction on these soft materials is feasible if proper methods are used. The fact that this complex structure was built in this era, is a testament to the genius of Canal designer and builders.

5.4 Navigation channels in the Sediments

Very soft sediments usually require very flat slopes to maintain their stability. Experience shows that commonly slopes (vertical: horizontal) of 1:3 or 1:4 are required. On occasions, flatter slopes may be required. However, since these slides are usually not critical, it becomes an issue of economy between initial costs and maintenance costs.

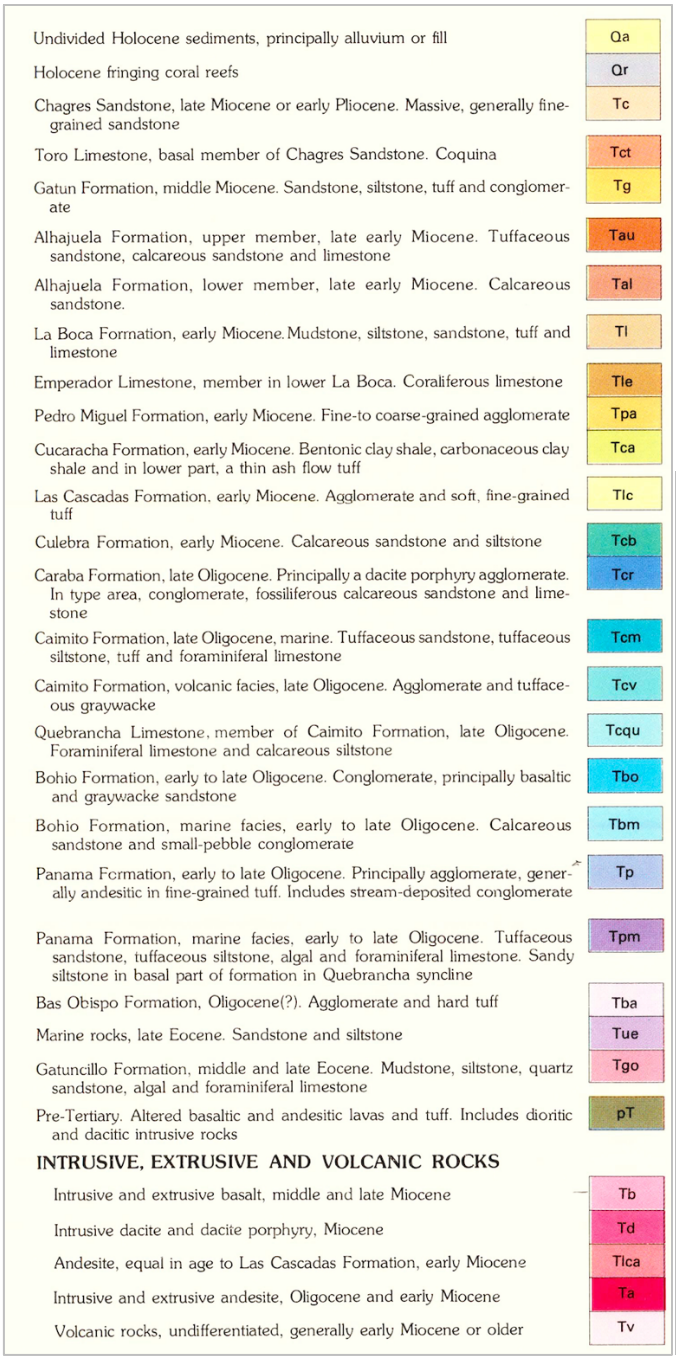
6. CONCLUSIONS AND RECOMMENDATIONS

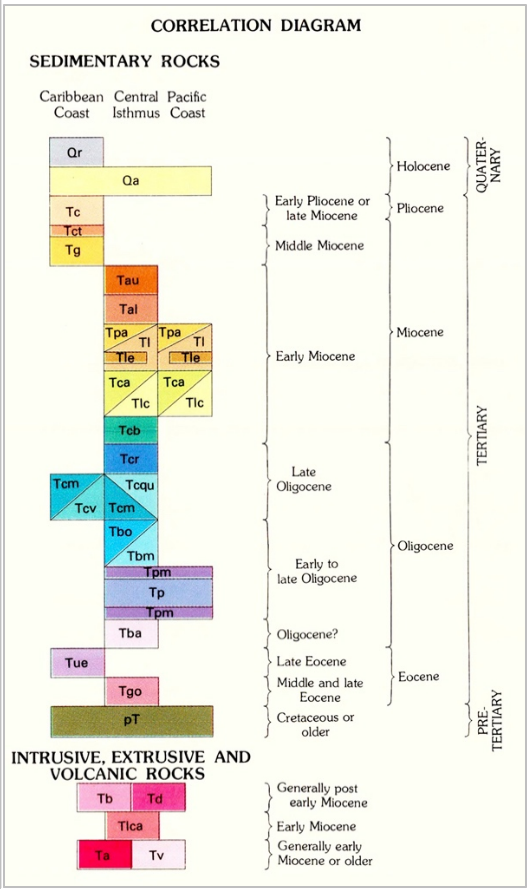
- Gatun formation materials have been used successfully in many large projects; as in-situ competent rock, and as compacted fills.
- Gatun formation materials constitute a promising resource for developing future engineering projects in the area. This paper describes its peculiarities, and recommendations for its effective use.
- The problems associated with the presence of soft sediments along the coast, can be mitigated if proper and proven procedures are used in design and construction.

Appendix A: Geologic legend and correlation diagram (15)

The geologic formations discussed in the paper are included in the following legend and correlation diagram for all the formations present in the Canal area.

LEGEND





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