ABSTRACT

During the last 20 years maritime traffic industry has changed tremendously. The exponential increase of cargo traffic between the different continents has led to the fact that shipping lines have been building vessels with larger dimensions. The actual Panama Canal and its locks are designed for vessels with maximum dimensions of 294.1 m (965 ft) long, 32.3 m (106 ft) wide with a maximum draught of 12.40 m (39.5 ft), the so-called Panamax vessels. Vessels that surpass these dimensions, the so-called post-Panamax vessels, can actually not transit the Canal.

As a result of the increased number of post-Panamax vessels and the increasing demand for Canal transits (according to market studies a gradually increase of 40% in demand for Canal transits up to 19,600 a year by 2025 is expected), the operator of the Canal, the Autoridad del Canal de Panamá (ACP), decided to give priority to increasing the Canal’s capacity as well as to the possibility for post-Panamax vessels to transit the Canal.

Under the expansion programme, the ACP called for 9 international tenders representing a total value of US$ 4.190 billion. This article elaborates on the execution of the “North Entrance Dredging of the Pacific Access Channel for the New Third Set of Locks” and, more specifically, on the challenges faced during the drilling and blasting operations required to execute the works.

INTRODUCTION

Since the first vessel SS Ancon officially transited the Panama Canal on August 15, 1914, a total of more than one million vessels have transited the Canal, approx. 14,000 vessels a year of which 13,000 are Ocean-Going Commercial Vessels.

During the last 20 years maritime traffic industry has changed tremendously. The exponential increase of cargo traffic between the different continents has led to the fact that shipping lines have been building vessels with larger dimensions. This tendency counts for all types of vessels, from oil tankers, to bulk carriers, from cruise vessels to, of course, container vessels. While in the mid-1970s the maximum capacity of container vessels was approximately 2,000 TEU (Twenty-foot Equivalent Unit), this capacity has today been increased to more than 14,000 TEU.

However, the actual Panama Canal and its locks (Gatun Locks, Pedro Miguel Locks and Miraflores Locks) (Figure 1) are designed for vessels with maximum dimensions of 294.1 m (965 ft) long, 32.3 m (106 ft) wide with a maximum draught of 12.40 m (39.5 ft), the so-called Panamax vessels. Vessels that surpass these dimensions, the so-called post-Panamax vessels, can actually not transit the Canal.

As a result of the increased number of post-Panamax vessels and the increasing demand for Canal transits (according to market studies a gradually increase of 40% in demand for Canal transits up to 19,600 a year by 2025 is expected), the operator of the Canal, the Autoridad del Canal de Panamá (ACP), decided to give priority to the increase of the Canal’s capacity as well as to the possibility for post-Panamax vessels to transit the Canal. These targets are included in the ACP’s Master Plan for the coming 20 years.

This Master Plan stands for an expansion programme that will double the capacity of
the Canal and allow post-Panamax vessels up to 12,000 TEU. It was approved by the Panamanian Cabinet and by the National Assembly in July 2006. The political decision was endorsed by the positive outcome of a national referendum held on October 22, 2006.

The total expansion programme consists of 4 major components:

- **Post-Panamax Locks**: Contraction of post-Panamax locks on the Pacific and Atlantic sides, allowing vessels with maximum dimensions of 366 m (1,200') long and 49 m (160') wide, having a maximum draught of 15.2 m (50').

- **Pacific Access Channel**: Excavation of the northern approach channel towards the new Pacific post-Panamax locks complex. Approximately 49 mio m³ along the 6.1 km northern approach channel is to be excavated.

- **Improvements to existing Navigational Channels**: Dredging of the existing channels (at the Atlantic and Pacific side) to enable the safe navigation of post-Panamax vessels through the expanded Canal.

- **Improvements to Water Supply**: Increase Gatun Lake’s maximum operating level by 45 cm to improve Canal Water Supply and draught dependability.

Under the expansion programme, the ACP called for 9 international tenders representing a total value of 4.190 billion US$:

- **Excavation of Pacific Access Channel Phase 1 (PAC-1)** – awarded July 17, 2007: Levelling of Paraíso Hill from 136 meters to 46 meters, meaning the excavation of 7.3 mio m³.

- **Excavation of Pacific Access Channel Phase 2 (PAC-2)** – awarded November 27, 2007: Excavation of 7.4 mio m³ of material, the 3.5 km diversion of the Cocoli River and the relocation of 1.3 km of the Borinquen Road.

- **Excavation of Pacific Access Channel Phase 3 (PAC-3)** – awarded December 18, 2008: Excavation of 8 mio m³ of material from Paraíso Hill, bringing down the level from 46 m to 27.5 m.

- **Excavation of Pacific Access Channel Phase 4 (PAC-4)** – awarded January 7, 2010: Excavation of 26 mio m³ of unclassified material, construction of a new 2.3 km Borinquen dam that will separate Miraflores Lake from the new channel.

- **Dredging of the Pacific Entrance Navigation Channel** – awarded on April 1, 2008: Widening the existing Pacific Access Channel to a minimum of 225 m and deepening to 15.5 m below mean low water level. Total dredging quantity of 8.7 mio m³.

- **Dredging of the Gatun Lake North Access Channel** – awarded June 4, 2010: Dredging a section of the Gatun Lake Access Channel. Total dredging quantity 4.6 mio m³.

- **Dredging of the Canal Atlantic Entrance** – awarded September 25, 2009: Deepening of the Atlantic Approach Channel to the New Set of Locks to 15.5 m below mean low water level. Widening (from 198 m to minimum 225 m) and Deepening the existing Atlantic Entrance Navigation Channel up to 16.1 m. Total dredging quantity of 17.1 mio m³ and an additional dry excavation quantity of 815,000 m³.


- **Dredging of the New Pacific Access Channel North Approach** – awarded August 16, 2010: This will link the new locks on the Pacific to the Culebra Cut.
Pacific Access Channel North Approach Project entails the dredging of the Pacific Access Channel North approach, which will link the new locks on the Pacific to the Culebra Cut. An area of approximately 26 ha needs to be excavated from the existing level of 27.5 m PLD (Project Level Datum) down to 9.14 m PLD. A total quantity of approximately 4,000,000 m³ needs to be removed.

The materials to be dredged range from weak to medium-hard rock type Cucaracha, to hard rock formations type “Pedro Miguel” and “Basalt”. The hard rock formations form approximately 75% of the total volume and need to be blasted before excavation. These blasting operations are very sensitive since the project area is located in the vicinity of residential areas and the Centenario Bridge and is adjacent to the Canal, where the traffic may never be interrupted.

All excavated materials need to be disposed of in 4 disposal areas: the onshore disposal areas Escobar, W4 and W5 and the offshore disposal area Peña Blanca, located in the Gatun Lake. The preparation of the disposal areas, including construction of dykes, is included in the scope of work (Figure 2).

**CHALLENGES**

**Rescue of local fauna and flora**
As defined in the Environmental Impact Assessment Studies of the Expansion Programme, the project requires a strong commitment from the contractor to protect and preserve the environment. ACP together with Panama’s National Environmental Authority (ANAM) constantly supervises the environmental measures taken by the contractor during the execution of the project.

**Excavation sequence**
Since the area to be excavated is connected with the existing Canal, the project will be executed by a combination of dry equipment and wet dredging equipment (Cutter Suction Dredger and Back Hoe Dredger). The challenge is to optimise the methodology and working sequence in order to offer the most economical execution method. Jan De Nul chose to execute a maximum quantity of material with dry equipment. The wet dredging equipment will be employed at the end of the project to excavate the remaining link (dykes) between the excavated area and the actual Panama Canal.

**Soil conditions**
At the tender stage ACP provided soil information including Cone Penetration Test (CPT) Results and Borehole information collected in the period between 1940 to 1971. The geological information from these CPTs and Boreholes indicated the presence of 3 different types of soil and rock formation, namely Cucaracha, Pedro Miguel and Basalt. In order to get more detailed information about the geology of the excavation area an additional borehole campaign was performed by the interested Tenderers.

Based on this additional information Jan De Nul Group made its own evaluation of the
geology and prepared a detailed geological map on which the excavation sequence and related modus operandi were determined. Four different soil types were identified: Basalt, Cucaracha, Pedro Miguel and Pedro Miguel Weak. Two of these soil types require blasting operations prior to excavation, namely the Pedro Miguel and the Basalt formation.

Drilling and blasting operations

Viewing the location of the areas where blasting operations should be performed (adjacent to existing Canal, Pedro Miguel Locks, under the Centennial Bridge and in the vicinity of the residential area Paraiso), these operations will require intensive monitoring (Figure 3).

The Canal traffic has an overall priority above all construction works and may not be stopped or interfered with.

Furthermore, to meet the maximum allowable limits with regards to vibrations and noise generated by the blasting operations and the required fragmentations would prove to be a challenging task.

Weather conditions

The dry excavation operations started mid-November 2010, exactly 90 days after Contract Award, in the middle of the rainy season. The absence of any hauling roads, the unavailability of suitable material to construct these roads, combined with an unprecedented precipitation in December 2010 of 1100 mm were a major point of concern (see Figure 4). Additionally, all water flowing from surrounding hills on the West side of the excavation area needed to be collected and drained off to the channel without hindering the excavation operations. Drain failure would entirely flood the excavation pits 2-N and 2-S.

PROJECT APPROACH / EXECUTION

Four Excavation Zones

In order to maximise the dry excavation volume to the final design level, the area is divided in 4 different excavation zones: 1, 2-N, 2-S and 3 (see Figure 5).

The following excavation sequence was determined:

1. Dry excavation till final design level (+9.14 m PLD) of Zone 2-N and 2-S
2. Dry excavation a layer of approx. 9 m (+18.5 m PLD) of Zone 1 and 3
3. Dredging the remaining layer of approx.
9m (from +18.5 till +9.14 PLD) by means of CSD Marco Polo and BHD Il Principe.

In order to excavate Zones 2-N and 2-S till the final design level, these areas need to be separated from the Canal Waters by a dyke and sufficient protection against water ingress for the Canal is required (Figure 6). The dyke between the Canal and the dry excavation areas exists of the material in Zone 3.

For the safety of the people and equipment in the excavation pit, 18 m below the canal, and to withstand the 18 m of water pressure on one side of the dyke, the engineering department of Jan De Nul Group calculated that the dyke should have a slope gradient of 1:4 in the Cucaracha material and a 1:2 slope in the Pedro Miguel material.

To optimise safety, 5 inclinometers have been installed in the dyke (Zone 3). This allows constant monitoring of possible settlements and/or slides in order to evacuate people and equipment on time.

**Four disposal areas**

Four disposal areas have been provided by the ACP:

- **W4**, at a hauling distance of 2 km:
  - a capacity 620,000 m³ for hard rock material

- **W5**, at a hauling distance of 4 km:
  - a capacity 2,800,000 m³ for all types of excavated material

- **Escobar**, at a hauling distance of 1 km:
  - a capacity 2,300,000 m³ for all types of excavated material

- **Peña Blanca**: a marine disposal area at the Gatun Lake that will be used to dump the material dredged by the Backhoe Dredger Il Principe. Sailing distance 36 km.

Because the Escobar disposal area is the nearest to the excavation/dredging area, this disposal area is used as the reclamation area for all material dredged by CSD Marco Polo. In order to prepare this area a containment bund is to be constructed to contain the material (Figure 7). Since the construction of this bund requires 550,000 m³, the total remaining reclamation capacity is reduced to 1,750,000 m³.

Taking into consideration an estimated bulking factor of 20% for the dredged material, this implies that only a volume of approximately 1,300,000 m³ can be dredged and reclaimed in this area.

The excavated material by dry equipment will be disposed of in disposal area W4 and W5 and will be used to construct the containment bund of the Escobar disposal area.
Excavation of Zone 1 and Zone 3
Zone 1 consists of Cucaracha material. Cucaracha material is weak to medium hard rock (UCSmax = 8 Mpa). This material does not require drilling and blasting operations and can be excavated or dredged immediately.

The volumes dredged by means of the cutter suction dredger are pumped in the Escobar Disposal area and are therefore limited to the capacity of this disposal area (Escobar disposal area had a limited total capacity of 2,300,000 m³, of which 550,000 m³ is already spent for dyke construction). Therefore the volume excavated directly by means of dry equipment will be maximised.

Excavation of Zone 2-North and Zone 2-South
Zone 2-North (Zone 2-N) and Zone 2-South (Zone 2-S) represent a total volume of 2,000,000 m³ (50% of the total volume to be excavated). Most volume in these zones, a total of 1,300,000 m³ out of 2,000,000 m³, is Basalt and Pedro Miguel rock formation implying drilling and blasting operations. The Pedro Miguel formation is a hard rock (UCSmax = 30-40 Mpa) and Basalt is very hard rock (UCSmax = 30-40 Mpa).

The rest of the volume consists of Cucaracha and Pedro Miguel Weak formation (UCSmax = 8 Mpa).

In order to excavate these zones a fleet of dry equipment was mobilised including:
- 2 excavators Liebherr 984
- 2 excavators Hitachi ZX-870
- Excavator Hitachi 470
- Excavator Caterpillar 336
- 20 Volvo A-40 Articulated Dump Trucks.
- 5 bulldozers Caterpillar D6 and D8
- 2 graders Volvo G-940
- 2 wheel loaders CAT-988

Excavation operations started in mid-November (Figure 8). Initially, the disposal areas had to be cleared and grubbed: All vegetation had to be removed and all wildlife encountered had to be relocated.

The actual excavation operations started one week later (Figures 9 and 10). Owing to the unprecedented rainfall during the months of November and December 2010, the level of the Gatun Lake reached alarm levels causing a closure of the Panama Canal during the first week of December for the first time in two decades.

Because of the adverse weather circumstances, multiple problems to prepare suitable hauling roads were encountered. Basalt was being ripped in order to install the much needed hauling roads and an extraordinary amount of time and energy was spent on constructing these roads.

Once suitable hauling roads were constructed, the excavation production increased considerably, reaching a daily production of up to 15,000 m³.
A 250-tonne Liebherr 9250 excavator was mobilised to Panama by Jan De Nul to optimise the land dredging in Zone 1. This equipment is equipped with a specially designed and manufactured, 14.8 m long boom and 9.45 m long stick. This boom and stick allow the excavator to excavate a maximum layer of 10.0 m. The remaining layer of 8 to 9 m will need to be dredged by the Cutter Suction Dredger *Marco Polo* and Backhoe Dredger *Il Principe*.

Upon completion of the dry dredging activities the CSD *Marco Polo* will dreg the lower layers of the Cucaracha material. This material will be pumped through the floating pipeline and landlines over a distance of more than 1 km to the Escobar disposal area. The encountered height difference between dredging level and disposal area is 50 m.

The lower layers of the hard rock formations Pedro Miguel in the Zone 3 will be dredged by means of the BD *Il Principe*, assisted by a float-top 3000-tonne barge and the self-propelled split-hopper barge *La Concepción*.

The float-top barge will transport all dredged material to disposal area W4. The split-hopper barge will discharge in the offshore disposal area *Peña Blanca* located in the Gatun Lake (sailing distance 36 km).

**DRILLING AND BLASTING**

Blasting is a key activity of the PENAC project. About 2,000,000 m³ of rock (Basalt and Pedro Miguel formation) need to be blasted, enabling the removal of the hard material later.

**Purpose**

The first purpose of blasting is to fracture the rock for excavation and transport. In order to excavate the blasting material by means of dry or wet excavation equipment, 99% of the blasted material must have a diameter of < 1m. Secondly pre-splitting and approximation blasting are used to create the final slopes. The contractual tolerance of the final slopes is 30 cm. Accurate blasting with a specially designed grid is needed to allow the excavation equipment to stay within these tolerances.

**Limitations for the blasting operations**

**Time frame**

The drilling and blasting operations are performed in sensitive areas (adjacent operational Panama Canal, nearby residential areas and Centennial Bridge). Therefore, in order to avoid disturbance and/or damage to existing constructions, stoppage of ongoing operations from Jan De Nul or other contractors, the planning of the operations is from the utmost importance and is followed up by project team and ACP representatives on a daily basis.

Blasts cannot be performed when a vessel is passing by at a distance of less than 450 m or when a ship is moored at the tie-up station of Cartagena which is situated at a distance of less than 450 m from the blasting area in Zone 2 South. Furthermore, blasting operations can only be performed in the time frame from Monday to Friday from 7 AM to 6 PM in order to avoid disturbance to the nearby community of Paraiso.

Vibration levels

Apart from the working time frames, ACP also imposed limitations on vibration levels during the operations in order to avoid damages to nearby structures. In the contract, the limitations of the vibration and air blast overpressure levels are set out according to USBM (United States Bureau of Mines).

In the Contract the following areas of concern with their specific limits of peak particle velocity during basting operations are mentioned:

(a) the face of the final slopes and benches; the existing Miraflares and Pedro Miguel lock structures; the Centennial Bridge and other nearby structures, shall not exceed a value higher than 25 millimetres per second (1 inch per second);
the vibrations:

Following empirical formula is used to predict the vibrations:

\[ v = k \cdot (Ds)^n \]

Where:
- \( v \) is the maximum expected peak particle velocity
- \( k \) and \( n \) are related to the ground characteristics, blast design, delay time, … and are determined by small test blasts in the field and by experience.

\[ Ds = \text{Scaled distance}: \]
\[ Ds = d / W^{1/2} \]
- \( d \) = distance to the nearest structure
- \( W \) = maximum charge per delay (A delay is the time between the detonation of 2 different charges.)

For the PENAC project the parameters of the model, determined by Jan De Nul and MESSA based on measurements of previous blasting operations with the pontoon Thor in the area, are:

\[ k = 500 \quad \text{and} \quad n = -1.2 \]

Consequently the following formula is used during the project:

\[ v = k \cdot (Ds)^n \quad \Rightarrow \quad v = 500 \cdot (Ds)^{-1.2} \]

The contractual limit for the air blast overpressure is 0.02 psi. Too high air blast pressure will provoke broken windows.

The blast vibrations (peak particle velocity, PPV) are monitored by seismographs (Figure 11). The seismographs are installed at the structures of concern to monitor the blast vibrations (Figure 12).

**Planning and design**

Based on the diameter of the drilled boreholes, type and quantity of explosives, the position of the boreholes and the vibration formula Jan De Nul designed the drilling and blasting pattern for each area.

There are 3 types of drilling and blasting operations to be executed in the PENAC project:
- underwater drilling and blasting;
- dry drilling and blasting in benches of 9 m;
- dry drilling and blasting in benches of 18 m;

**Underwater drilling and blasting**

The underwater drilling and blasting operations were performed in the outer slope towards the Panama Canal of the working area.

The ACP provided the drilling and blasting pontoon Thor for 2 months from 1 December 2010 until 31 January 2011. The pontoon is equipped with 4 drilling rigs working simultaneously. The drill diameter is 6.5 inch (Figure 13). Additionally, the ACP provided...
cartridges (3.2 kg each) per hole or an average charge of 118.4 kg per hole were used.

The most adjacent structure is situated at a distance of 230 m. Based on the prediction formula, the PVV at the closest structure is:

\[ v = 500 \times \left(\frac{239}{118.4^{1/2}}\right)^{-1.2} = 12.4 \text{ mm/s} \]

Since this value was close to the limit of 12.7 mm/s, a test blast was performed with a reduced charge to verify the predictions. The test showed that the predictions were on the safe side and the second test blast with the complete charge was performed. The results of the measured PVV (with a result of 10.4 mm/s) were less than the predicted value and stayed far below the accepted values.

Furthermore a powder factor (explosives (kg) / volume of rock (m³)) of 0.75 kg/m³ was chosen to come to the required fragmentation. This information was based on the experience of the involved parties.

The last step in the drilling and blasting process was to determine the spacing between the different boreholes. Based on the powder factor and the vibration limits a drilling pattern of 3.25 m by 3.25 m was performed.

An average borehole consisted of a depth of 14.8 m. The Emulsion cartridges are 0.4 m large so either an average number of 37 cartridges (3.2 kg each) per hole or an average charge of 118.4 kg per hole were used.

All 15 blasts were performed within 1.5 months without problems. A total 4,484 meters were drilled. The total amount of explosives used was 29,033 kg to blast a rock volume of 34,886 m³. This gave an overall powder factor of 0.83 kg explosives/m³ of rock, which is a bit higher than the originally foreseen powder factor. The fractured material will be removed by means of the BD il Principe early 2012.

Dry drilling and blasting in benches of 9 m Zones 2 North and 2 South are excavated by means of dry equipment. In Zone 2 North the Pedro Miguel formation and in Zone 2 South the Basalt formation needs to be blasted. The excavators usually excavate the material in benches of 4.5 metre. However, the cost for blasting in 4.5 metre is too high (more...
blasting, smaller drill holes, more explosive devices, etc.). Therefore it was decided to opt for blasting benches of 9 metre.

A thorough survey of the rock structure and characteristics (fissures, homogeneity, rock strength) is primordial in order to be able to determine the methodology, the planning and the drilling and blasting pattern. Hard to predict are the physical and mechanical characteristics of the rocks. Not a single prediction model is entirely accurate. Luckily, blast software is available which helps to design the blasting patterns. Still, an experienced blaster is indispensable to interpret the parameters correctly.

Blasting in benches of 18 m
The Pedro Miguel formation in the dyke (Zone 3) is to be blasted in 1 time in 18 m, because the area will be underwater once the first metres are excavated. This area stays in connection with the Canal. The design shall be the same as the 9 m benches, with one exception: The charges will be divided in 2 (double deck) by means of stemming material in the middle of the hole to reduce the charge per delay.

ROCK CHARACTERISTICS
Rock is a general term for hard material. To prepare a good blasting pattern it is important to include the correct characteristics for the material to be blasted in the design and to choose the correct explosives. The most important characteristics of the rock influencing the blasting result include:
- tensile and compressive strength,
- density and
- seismic velocity (acoustic velocity).

Tensile and Compressive Strength
Most types of rock have a compressive strength which is 8 to 10 times greater than the tensile strength. The explosives must produce enough energy to surpass the rocks’ compressive and tensile force (see Table I).

Density
High density rock is normally harder to blast than low density rock, because high density rock is heavier to move during detonation.

Seismic Velocity
The seismic velocity is the speed of a wave going through a medium. The seismic velocity (acoustic velocity) of the various types of rock varies from 1500-6000 m/s. Hard rock of high seismic velocity will crush more easily, especially when explosives having a high velocity of detonation are used (see Table II).

The Basalt formation to be excavated in the project area has more or less the same parameters as granite mentioned in the different tables. Whereas this formation contains some silt fragments as well as some fault lines mostly oriented from north east to south west, it is generally a high density rock formation.

The Pedro Miguel formation is softer and can be categorised as a cemented claystone. More cracks are present and the density is lower than the basalt.

CHOOSING THE EXPLOSIVES
Different types of explosives are available on the market. Depending on the rock characteristics and the blast design the most effective type of explosive had to be chosen. The characteristics of explosives that have been taken into account are described below.

Sensitivity
This characteristic defines the ability of the explosive to propagate a stable detonation through the entire length of the charge. The critical diameter (below this diameter the explosive will not detonate reliably) is an indication of the sensitivity: the higher the sensitivity the smaller the critical diameter.

Water resistance
Some explosives (e.g., ANFO, a mixture of Ammonium nitrate fuel oil) have very poor water resistance and cannot be used if the boreholes contain water. Other explosives (e.g., emulsions, nitrates with oxidisers in a water oil mixture) are well resistant to water and can withstand long periods in water.

There are 2 types of water resistance: internal and external. Internal water resistance is water resistance provided by the composition of the explosive itself. External water resistance is the water resistance provided by the packaging or cart ridging in which the explosive is placed. In any case, the time exposed to water should be kept to a minimum for each explosive.

Pressure tolerance
When boreholes are deeper than 5 m, hydrostatic pressure occurs. Additionally, dynamic pressure may occur from detonation in adjacent boreholes. When the pressure becomes too high the explosives become too dense and refuse to detonate.

Fumes
The released amount of toxic gasses when blasting is to be minimised. The most common
gases considered in fume class ratings are carbon monoxide and oxides of nitrogen. Commercial explosives are made to get the most energy out as possible while minimising these gases. This is done by balancing the oxygen in chemical reaction of the explosive.

**Thermal stability**

Temperature fluctuation influences the sensitivity of the explosives. If temperature rises too high, the explosives may deflagrate. If temperature drops too low, the explosives lose sensitivity.

The Performance Properties of the explosives are: Sensitivity, velocity, detonation pressure, density, and strength.

**Sensitivity**

The sensitivity of an explosive product is defined by the amount of input energy required for the product to detonate reliably. In commercial use the explosives have low sensitivity and they need a booster/primer, detonator or detonating cord to be detonated.

**Velocity**

The detonation velocity (VOD) is the speed of which the detonation runs through the explosive. The higher the VOD the more shock wave energy is created (more energy released in the same time) and the heave energy will be lower. These explosives are ideal for very hard rock (Granite). For weaker rock more heave energy is needed since the shock wave energy is partially absorbed by the softer rock mass.

**Detonation Pressure**

The detonation pressure is the pressure associated with the reaction zone of a detonating explosive. In hard and competent rocks the fragmentation is done more easily with high detonation pressure explosives, owing to the direct relationship that exists between detonation pressure and the breakage mechanisms of the rock.

**Density**

The density of an explosive is important because it determines the total weight of explosives which can be loaded in the borehole with a specific diameter. Based on this the Powder factor (Explosives (kg) / cubic meter of rock (m³)) can be determined and the drilling pattern adjusted.

**Explosives for PENAC Project**

In the PENAC project Emulsion and ANFO (Ammonium fuel oil) were chosen as the explosive. Since they are primer sensitive explosives (they need a booster to be detonated), it is a safe product to work with, because there is no risk of accidental detonation by friction or impact.

Only the high energy of a booster (PETN: High explosive) will detonate the ANFO (Figure 14). The emulsion is water resistant and mixed with the ANFO it reaches high detonation velocities up to 5,200 m/s.

**EXECUTION OF BLASTING OPERATIONS**

From blast experience throughout the years, numerous empirical formulas and models have been developed. Despite the existence of formulas and models, experienced blasting staff is required to apply these rules optimally. Still “Trial and Error” is part of the start-up process.

In the case where a bench height of 9 m is required, the borehole diameter is determined by following formula in Table IV.

Based on this formula the diameter of the borehole should be 4.5 to 5.5 inch. For the PENAC project, a borehole diameter of 5 inch and an emulsion-ANFO mixture of 70%-30% were chosen. Variation of parameters with strength of the rock based on the diameter (in cm) of the blast hole is shown in Table V.

The burden (distance between the first blast hole and the free face) for the onshore blasts is determined to be 4.5 m (≈35*D = 4.44 m). The spacing or the distance between holes is determined to be 5.5 m (≈43*D = 5.46 m).
The stemming was determined to be 0.7 times the dynamic burden or more. For the blasts of 9 m benches, 3.20 m of stemming is used. This stemming is very important to keep the energy of the blast inside the blast area, to avoid flyrock, air-blast overpressure, too high vibrations, and so on. One metre sub-drilling is required to make sure that everything is blasted to the desired level. Blasts of 30,000 m³ are performed 2 times a week (Figure 15).

An electronic detonating system (Figure 16) as initiation system or detonator was chosen. Electronic detonators are very accurate and no or very few misfires happen. The blast sequence (delays between the different detonations) is programmed in the detonators. This sequence is important to maximise the fracturing and minimise the vibrations.

Once the blasting pattern is set, the drilling works start by means of 2 mobile drilling rigs type Furukawa HCR 1500 (Figure 17). The drilling speed is about 35-40 m/h.

The drilling, using both rigs, takes about 3 days for 1 blast of 30,000 m³. In total, about 130 holes of 10 m deep are drilled for 1 blast.

Table I. Compressive and tensile strength of rock materials.

<table>
<thead>
<tr>
<th>Type of rock</th>
<th>Compressive strength (kg/cm²)</th>
<th>Tensile strength (kg/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granites</td>
<td>2,000 – 3,600</td>
<td>100 – 300</td>
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<tr>
<td>Diabase</td>
<td>2,900 – 4,000</td>
<td>190 – 300</td>
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<tr>
<td>Marble</td>
<td>1,500 – 1,900</td>
<td>150 – 250</td>
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<tr>
<td>Limestone</td>
<td>1,300 – 2,000</td>
<td>170 – 300</td>
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<tr>
<td>Shale</td>
<td></td>
<td>300 – 1,300</td>
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<tr>
<td>Sandstone, hard</td>
<td>3,000</td>
<td>300</td>
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</tbody>
</table>

Table II. Density and seismic velocity of rocks.

<table>
<thead>
<tr>
<th>Type of rock</th>
<th>Density (kg/dm³)</th>
<th>Seismic velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Granite</td>
<td>2.7 – 2.8</td>
<td>4,500 – 6,000</td>
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<tr>
<td>Gneiss</td>
<td>2.5 – 2.6</td>
<td>4,000 – 6,000</td>
</tr>
<tr>
<td>Limestone</td>
<td>2.4 – 2.7</td>
<td>3,000 – 4,500</td>
</tr>
<tr>
<td>Dolomite</td>
<td>2.5 – 2.6</td>
<td>4,500 – 5,000</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1.8 – 2.0</td>
<td>1,500 – 2,000</td>
</tr>
<tr>
<td>Clay mudstone</td>
<td>2.5 – 2.7</td>
<td>4,000 – 5,000</td>
</tr>
<tr>
<td>Marble</td>
<td>2.8 – 3.0</td>
<td>6,000 – 7,000</td>
</tr>
<tr>
<td>Diabase</td>
<td>2.8 – 3.1</td>
<td>4,000 – 5,000</td>
</tr>
</tbody>
</table>

When 80% of the drilling holes for the blast are ready, the installation of the explosives starts. A truck filled with explosives arrives on site (Figure 18). The truck contains 3 reservoirs: one for ANFO, one for Emulsion, and one for water and a safe locker for the boosters and detonators.

After an initial meeting, a team of 10 to 12 people starts to divide the electronic detonators and the boosters along the holes. The blaster connects the electronic detonators with the booster and lowers them into the blast hole. The operator of the truck is informed which charge is needed for each hole. The correct amount of explosives is prepared in the truck and then the truck starts pumping the explosives in the hole.

As well a visual verification is done by the blast master to prevent mistakes in the charging of the holes.

The next team follows to put the stemming (Gravel stones). This is the last but very important step for the loading. If the stemming is not correctly put, the gravel will be blown out of the hole. This creates flyrock and the energy of the explosion is lost.

When the holes are stemmed, the blaster reads the barcodes on the electronic detonators and gives them the correct delay times. The electronic detonators are connected to the wire and the whole blast connection is checked on the control box.

For safety reasons, the blast area is evacuated and the roads are closed in a radius of 500 m. All operations by all contractors are stopped. When the area is cleared, the final process can start. The ACP Contracting Officer Representative communicates with ACP Canal operations to avoid any disturbance with the canal traffic. The moment that all ships are clear and the canal operations give their...
approval a first horn signal is given. After a second check for safety, the blast master arms the electronic detonators.

After 5 minutes the second horn signal is given. One minute later the blast master pushes the button for detonation (Figure 19). Only 5 minutes later the blaster can go back into the blast area (when toxic fumes are gone) and check if all holes were detonated. If every hole is safe, dry excavation equipment can start digging.

Table III. Properties of Ammonium Nitrate Fuel Oil (ANFO).

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Empirical</th>
<th>PENAC 9 m bench</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emulsion (%)</td>
<td>25%</td>
<td>40%</td>
</tr>
<tr>
<td>ANFO (%)</td>
<td>75%</td>
<td>60%</td>
</tr>
<tr>
<td>Density (g/cc)</td>
<td>1.17</td>
<td>1.30</td>
</tr>
<tr>
<td>VOD ft/s (1000s)</td>
<td>13</td>
<td>16</td>
</tr>
<tr>
<td>m/s (1000s)</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Water Resistance</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>REE§</td>
<td>114</td>
<td>176</td>
</tr>
<tr>
<td>Minimum Diameter (Inches)</td>
<td>5&quot;</td>
<td>5&quot;</td>
</tr>
</tbody>
</table>

Table IV. Empirical relation of borehole diameter and bench height.

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Very High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borehole diameter</td>
<td>D = 0.001 – 0.002 H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.5 in (11.43 cm) – 5.5 in (13.97 cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table V. Empirical relation between drill diameter and burden and spacing.

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
<th>Very High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burden</td>
<td>B 39 x D</td>
<td>37 x D</td>
<td>35 x D</td>
<td>33 x D</td>
</tr>
<tr>
<td>Spacing</td>
<td>51 x D</td>
<td>47 x D</td>
<td>43 x D</td>
<td>38 x D</td>
</tr>
</tbody>
</table>

CONCLUSIONS

The execution of the PENAC project or “Pacific Entrance North Approach Channel” or “Dredging of the New Pacific Access Channel North Approach Project” requires a whole variety of activities – excavation, drilling and blasting, dredging operations, dyke construction…. Especially the extensive blasting operations were challenging and a great deal of technical expertise was necessary. Broad experience was built up in a very short period.

Additionally, the project is subject to the demanding restrictions of the nearby operational Panama Canal, the communities and neighbouring contractors. This all requires detailed preparations, thorough planning, and adequate mobilisation strategy and the appropriate equipment choice.

Together with the good co-ordination amongst all partners and the different departments (engineering, survey, civil construction, dredging and technical departments), the project team has taken on the challenge successfully and at this moment the project is more than one month ahead of schedule, on track for an early completion in November 2012.

REFERENCES


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