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Marine Environmental Control Strategies for Underwater Blasting Works in Sepetiba Bay, Brazil

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Abstract— The rise of environmental concerns demands effective measures to control and mitigate undesired impacts in infrastructure projects. In the case of hard-rock dredging works, where underwater blasting techniques are needed, the presence of sensitive structures and protected environmental areas are conditional factors for sustainable design of the works. This makes the control of the undesired blasting effects, such as ground vibrations and hydraulic shock waves, extremely important. The understanding of such phenomena and how to mitigate them, are key for an effective marine environmental control. Thus, this paper discusses some of the main strategies used to minimize blast undesired effects from a project carried out in Sepetiba Bay, Brazil.

Index Terms— Underwater blasting, vibration, hydraulic shock waves, marine environmental.

1 Introduction

THE world is more connected than never. A continuous flux of goods is moving every day into difference parts of the globe. This transportation phenomenon demands huge infrastructures, which includes ports, navigation channels, and others. The increasing of vessels' size and international commerce are the main reasons for most of the efforts for deepening and widening the antique harbor and ports around the world.

The construction and maintenance of these infrastructure utilities usually require the use of special excavation techniques when the material to be excavated is hard enough for traditional dredging equipment. In these cases, the use of underwater blasting techniques to fragment the rock into particles of a specific size, in order to optimize the dredging of the blasted material, are a fundamental stage in many constructions works like deepening navigation channels, excavations for pipelines or communication cables, demolition of structures, among many others [1, 2].

However, underwater blasting works are frequently carried out in places where the environmental concerns are critical. Protection of sensitive structures and mitigation of the potential impact on the marine life are the most common demands from authorities and local communities. This makes the control of the associated environmental effects, such as ground vibrations and hydraulic shock waves, extremely important. Thus, in this paper, a general overview over the main aspects associated with these environmental adverse effects are discussed under the view of an underwater blasting project carried out in Sepetiba Bay, in Brazil.

2 Environmental Adverse Effects

In underwater blasting, a fraction of the explosive's energy manifests in form of seismic excitation, which generally include ground vibration, air-blast overpressure and hydraulic shock waves.

However, air-blast does not represent a critical problem in underwater operations, except for those shots with lower water column. On the other hand, ground vibrations and hydraulic shock waves are generally a huge challenge for the project since most underwater works are considerable close to sensitive structures such as docks, quay walls, port facilities in general and, in many situations, fully urbanized areas. This makes the control of the associated environmental effects particularly important [1, 3, 4].

2.1 Ground Vibrations

Ground vibrations induced by underwater blasting are considered more dangerous than vibrations induced by traditional blasting due to the combination of ground waves and water borne shock waves [1]. Their effect on land is often accompanied by low frequency components, which increases the risk of damage to civil structures [3, 5].

The ground vibration formula [6], based on the square roof scaled distance relationship, can be statistically modelled with the following equation

$$PPV = K\left[\frac{D}{Q^{1/2}}\right]^{\beta} \quad (1)$$

where PPV is the peak particle velocity; Q is the maximum instantaneous charge; D is the distance; K and β are site-specific constants, to be determined by statistical analysis.

In general, the values of K and β vary with the type and properties of propagation medium, blasting geometries, timing and orientation, confinement, type of explosive and range of the data under analysis. Over the years, several authors have published vibration prediction formulas and experimental results [7, 8, 9, 10]. Usually, the value of K describes the vibration intensity. This factor is influenced by several factors including geology, confinement, coupling, rock strength and others. On the other hand, the attenuation factor β describes how fast the propagation medium absorbs the seismic energy with the distances.

2.2 Hydraulic Shock Waves

Underwater blasting techniques require the application of ex-

ISSN 2229-5518

plosive charges into boreholes with the aim of fostering a satisfied process of rock fragmentation. As consequence of this confined underwater detonation, a portion of the explosive's energy is perceived as hydrodynamic shock waves, which are potentially dangerous for the marine eco-system. It presents a very large radius of action, the risk of damage for nearby ships, quays and/or harbor installations and, even more important, the potential mortality of fishes and mammals, and other protected species, are real concerns.

The main factors that contribute to the generation of hydrodynamic shock waves by confined charges are the size of the charge, loading and depth of the confining material, blast geometry and initiation sequence, physicochemical properties of the explosive, the geometric shape of the explosive charges, and mitigation systems and materials used, among others [2].

Gil'manov [11] indicates that only a portion of the charge close to the borehole collar contributes to the peak pressure generated by the hydraulic shockwaves. Thus, the proposed expression to estimate the peak pressure from confined borehole charges in underwater detonation, which adapting for any type of explosive, is

$$P_{HC} = 70\ G_{at}\left[\frac{R}{W^{1/3}}\right]^{-2.0}\left(\frac{L_C}{5D_C}\frac{115}{RWS}\right)^{-2/3} \qquad (2)$$

where P_{HC} is the peak pressure of the confined hydraulic shock wave; Gat is the attenuation factor of Gil'manov; R is the distance; W is the mass of explosive charge; Lc is the charge length; Dc is the borehole diameter; RWS is the Relative Weight Strength relative to ANFO (ANFO=100%).

The equation (2) can be used to estimate the maximum expected peak pressure generated by hydraulic shockwaves from confined (buried) charges in boreholes.

2.3 Planning the Marine Environmental Control

All these potential adverse effects shall be analyzed in detail by experts in order to define a strict strategy and protocol to eliminate, control or minimize possible damages on the marine wildlife and surrounding islands structures. Involving environmental agencies and authorities, a part of a dedicated team of technicians and biologists, in charge of all monitoring programs, the blast protocol must be successfully implemented and conducted during the execution of the project, with total transparence between involved parties.

Thus, the marine environmental control protocol shall include the following actions: (a) suspended charges before the main detonation; (b) installation of acoustic devices to scare fishes and mammals; (c) stemming all boreholes; (d) use of burble curtain around of the detonation; (e) use of warnings sirens before, during and post-detonation; (f) full monitoring of ground vibrations and air-blast overpressure; (g) full monitoring of hydraulic shock waves and underwater noise; and (h) perform visual monitoring of areas around detonation.

3 Sepetiba Bay Project

A new private port terminal, called Porto Sudeste do Brasil, was recently inaugurated in Madeira's Island, located in Sepetiba Bay, south of the city of Rio de Janeiro, Brazil. Designed to handle and export Brazilian's iron ore and other bulk solid cargoes to international markets, this strategic port terminal is connected with the iron ore quadrangle in Minas Gerais State via private railway, giving Brazil's independent miners seamless logistic access to global markets.

Hard rock dredging excavation with underwater drilling and blasting techniques was required as part of capital dredging works for the deepening and widening of the access channel and turning basin of the Sudeste Port Terminal. However, the site was inserted in a demanding and protected marine environmental area, at Sepetiba Bay (Figure 2), which required a strong environmental program in order to control and minimize undesired effects such as hydraulic shock waves and ground vibrations in surrounding islands.

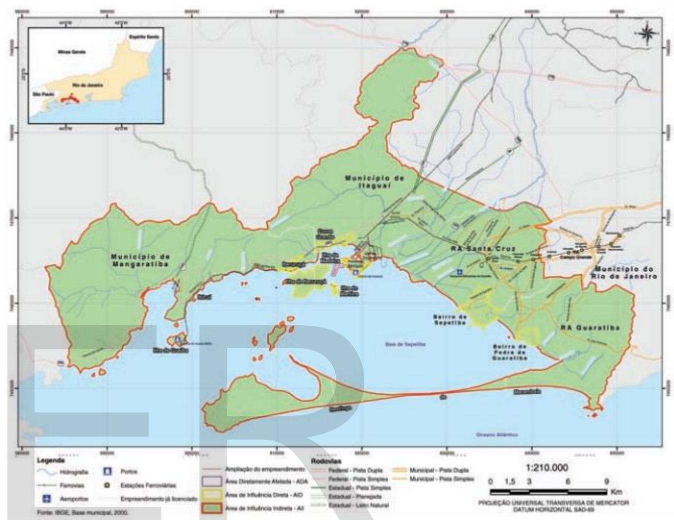

Fig. 2. Project Location at Sepetiba Bay, an environmental protected area.

The work consisted of removal of 245.000 m3 of bedrock by means of underwater drilling and blasting techniques. The objective was the excavation of the access channel and turning basin for a final navigation depth of -20m with minimal or no disturbances to surrounding islands and marine environment. In order to execute this task, the site area was divided in 8 different smaller work zones in affinity with geologic formation and project schedule. In the total, 62 detonations were performed, consuming up to 600 tons of explosive. Some of these zones required special attention in terms of blasting techniques either due to ground vibrations limits or problematic geological formations, or both.

Moreover, a special and strict blasting protocol was prepared in order to put in place all mitigation and control measures to guarantee minimum or no environmental disturbances. This protocol included – among many other details – internal and external communications, safety and security of the blast area, mammal observations by biologists, pre-blast preparations by scaring fishes and mammals with suspended charges, underwater sirens and pingers to repel fishes, burble curtain, installation of hydrophones and seismographs, and others. By following this strict protocol, the culmination moment of the blast, firing the blast itself, could be safely executed [12].

ISSN 2229-5518

3.1 Modelling and Contorlling Ground Vibrations

The so-called Z1 area was the most critical work zone of the whole project. Difficulties emerged from the associated risk of generating higher ground vibrations on the island "Ponta da Boi" (Figure 4) and the complex geologic structure, formed by natural boulders and caves. Furthermore, the rock layer to be excavated close to channel limits required boreholes up to 14m depth, which strongly increased the overall difficulties due to the limitations imposed by the maximum instantaneous charge.

Fig. 4. General overview of one of the shots carried out at Z1 area.

In order to affront this scenario, an exhaustive Test Blasting Program was planned and executed in order to obtain a proper in-situ vibration data to establish the local attenuation laws before the production blasting phase (Figure 5). One of the results of this site-specific study was the determination of the maximum allowed instantaneous charge for each shot in the project, especially in this area, by taking into account the real distances from blast areas and sensible structures.

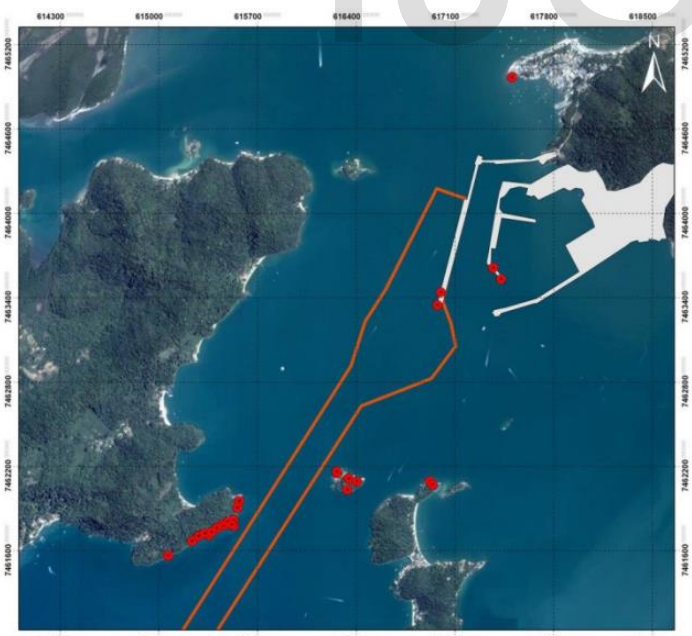

Fig. 5. Ground vibration monitoring locations (red points) along all surrounding islands and port structures

Statistical regression techniques were used in order to obtain the site-specific attenuation law for the "Ponta do Boi" island. Thus, for a 50% confidence interval, we had

$$PPV_{50\%} = 1108 \left(\frac{D}{Q^{1/2}}\right)^{-1.593} \quad (3)$$

However, for safety reasons, the confidence level was increased up to 95%, giving the following formula

$$PPV_{95\%} = 2666 \left(\frac{D}{Q^{1/2}}\right)^{-1.593} \quad (4)$$

The model represents a coefficient of determination R2 of 79%, which means that 79% of the points could be explained by the model. Once obtained, the ground vibration law was used to simulate in advance each of the production blast and, then, evaluate if the proposed blast design satisfies all specifications imposed by the ground vibration limits (Figure 6).

Fig. 6. Isoline of ground vibrations around of the blast. Z1 Area.

Exhaustive simulations regarding to the expected ground vibration were done in each blast in order to stablish the best technical solution. As part of these simulations, the interaction of front waves (Figure 7) was modeled out by considering the seismic velocity of the medium, delay times, initiation sequence, ground vibration law of area and the position of each borehole. This type of analysis allows the evaluation of possible wave's constructive interferences, by identifying directions where the risk of overlap's waves was higher and, as consequence, increasing the risk of higher vibration peaks. Consequently, in case of any sensitive structure was laying on this direction, a new simulation could be performed in order to restudy the initiation sequence to obtain the best combination of delays and initiation points for that particular shot.

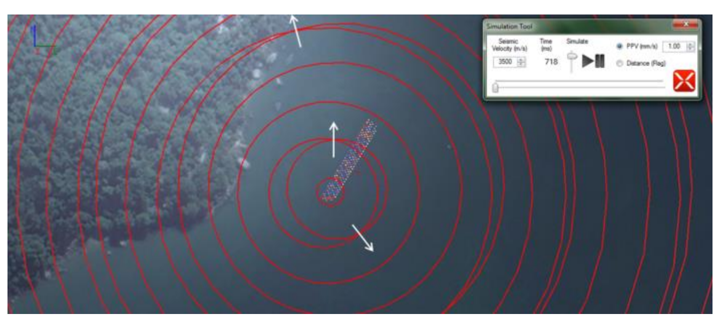

Fig. 7. Front waves superposition analysis in order to define the blast delay and initiation sequence of the blast. Z1 Area.

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3.2 Hadling Hydraulic Shock Waves

The Sepetiba Bay is the residence of Tucuxi Dolphins (Sotalia guianensis), a protected marine mammal species, and migratory cetaceans such as humpback whales (Megaptera novaeangliae) [12]. Thus, due to the biological significance of the region, the control and minimization of hydraulic shock waves was strongly necessary. Figure 8 shows some Tucuxi Dolphins around of blasting areas.

Fig. 8 Sotalia guianensis, one of the protected mammals at Sepetiba Bay. Locally called as Boto-Cinza (Gray-Dolphins).

Simulations of the expected hydraulic shock pressure peak were carried out using the equation (2). Figure 9 shows the prediction of the 100kPa isoline around the planning blasting at N4 area.

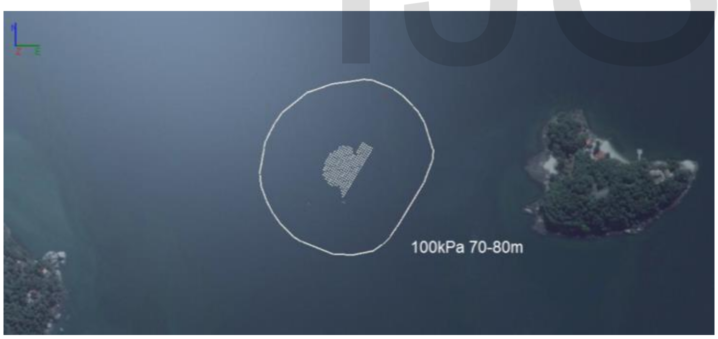

Fig. 9. Expected radio of action for hydraulic shock waves of 100kPa for the area N4.

Additionally, hydrodynamic shock waves were monitored with special autonomous hydrophones, which were installed in strategic points around of the detonation areas. Results of this monitoring program showed a general trend from near-to-constant to slight increase between underwater peak pressures and the maximum instantaneous charge (MIC). This behavior was somehow expected. A direct analysis between MIC and hydrodynamic peak pressures by their own is not enough to have a complete understanding of the confined charge detonation phenomena, since just the superior portion of the borehole – close to the stemming – effectively contributes to the measured values of hydraulic shock peak pressure – excluding the seismic transmission from rock medium to water.

Another important aspect was the stemming effect on peak pressure of hydrodynamic waves. The importance of this parameter on the hydrodynamic pressure is more than significant. A proper stemming design should avoid the direct transmission of the explosive's energy to the water, decreasing the level of hydraulic peak pressure, and to control the frequency components in land vibrations. Thus, as the stemming length increases, smaller hydraulic peak pressure is generally expected [11, 13, 5, 4].

A part of blast design improvements, such as the control of stemming and maximum instantaneous charge, additional techniques were deployed in order to minimize damages for the marine life. A cetacean monitoring program was deployed in order to maximize the control over the presence of marine mammals and minimize their potential mortality, which includes Mammal observation activities, the use of acoustic repellents and suspended charges and the use of bubble curtains. These measures [12] are briefly discussed as follows:

1) Mammal observation program:

Starting 1h before the main detonation, continuing up to 30 min after the clearance of the blast. At this stage, biologists need to confirm the absence of cetaceous during the last 30 minutes before blast. If any marine mammal was observed entering in the exclusion zone of 1000m, the detonation process was immediately stopped until they left the area.

2) Aacoustic repellents:

This technique was used in order to improve the control of fish and mammal concentrations in the immediate vicinity of the blast. For that task, ten acoustic deterrent devices called pingers were systematically installed around of the detonation area to create a 750m exclusion zone. These devices were activated 40 minutes before the main detonation. In addition, a SPA (Sound Projector Array) was installed 1h30 min before, being activated until the bubble curtain activation. The use of a continuous noise source can potentially reduce the impact on the marine life by underwater blasting operations due to its effective repelling effects on fishes and mammals for a time enough to isolate the blasting area by the air bubble curtains.

3) Suspended Charges:

Three suspended charges were detonated minutes before the activation of the bubble curtain and the main detonation in order to scare the fishes and cetaceans from the blasting area.

Fig. 10 Burble Curtain placed around of the blast area.

4) Bubble Curtains:

One of the main efforts to prevent fish and cetaceans mortality was the use of bubble curtain to isolate the blasting zone from the vicinity area (Figure 10). The effectiveness of this technique is based upon the reduction of the peak level of the hydraulic shock wave outside of the curtain perimeter. Bubble Curtain aims to attenuate the sound dispersion in the aquatic environment and its activation starts after 30 minutes of visual monitoring that proves the absence of cetaceans in a radius of 1 km from the site of overthrow and 20 minutes before the main detonation.

4 Conclusion

The main strategies of modelling, mitigation and control of undesired underwater blasting effects, such as ground vibrations and hydraulic shock waves, were discussed. Special blast designs are required to ensure safety of sensitive structures and to protect marine species surrounding of the blast areas. The conscientious implementation of a marine environmental program is essential for the success of any hard-rock dredging project. A special case study was presented, where underwater blasting works were carried out under a demanding environmental condition. Finally, the main fundamentals of marine environmental control for sensitive structures and marine species were discussed.

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