Ground Vibrations & Water Borne Shock Waves Caused due to Underwater Blasting in Ports – A Case Study

V. Rama Sastry, G. Raghu Chandra, and C. Karthik

***Abstract*— Underwater drilling and blasting is adopted in ports as a part of capital dredging. Underwater blasts affect the ambient environment in terms of ground vibrations and water borne shock waves. Knowledge regarding the pressure due to each underwater blast can help us monitor the safety of structures and workers or other aquatic life. Deepening of draught was carried out in the entrance channel / and turning circle of outer harbour in Vishakhapatnam Port, Southern India, involving underwater blasting in about 2,50,000m2 area, for a depth of 8m. Blasts were designed to ensure safety of various structures in the port and its efficacy was established by monitoring of blast vibrations at different structures. The paper describes the methodology adopted, equipment used and various steps taken in the safe execution of the rock dredging project. The paper also discusses the calculation of safe distance from environmental and worker's safety aspect for the safe execution of the rock dredging projects.**

***Keywords*— Ground Vibrations, Rock Dredging, Safety, Underwater Blasting, Water Borne Shock Waves.**

I. INTRODUCTION

Fragmentation of hard sea bed rock by underwater blasting is a vital operation in rock dredging projects. While desirable results are good fragmentation and throw of fragmented material, the undesirable effects include damage to surrounding structures, accident to workers in vicinity and harmful effect on surrounding marine flora and fauna. The safety aspects of underwater blasts should ensure that these undesirable effects are minimized. To check or ensure that the structures /and vessels surrounding are safe during the blast, the PPVs of generated ground vibrations are monitored. The protection of various marine species both flora and fauna, divers operating in the location is also of utmost importance from the environmental and safety point of view. The pressure of the water waves generated due to shock waves of blast is monitored and the safe distance is established prior to conduct of blast. Based on these data, sufficient precautionary actions and warning can be given to protect the divers and marine life in the vicinity of blast.

II. LITERATURE REVIEW

A. Ground Vibrations

When the intensity of strain waves generated due to detonation in a blasthole, diminishes to the level where no permanent deformation occurs in the rock mass, i.e. beyond the fragmentation zone, strain waves propagate through the strata in the form of elastic waves. These waves in the elastic zone are known as ground vibrations [1]. Ground vibrations may cause structural damage and annoyance to public, while damage to nearby structures/ vessels and marine life may be caused by excessive underwater shock waves. Whenever blast vibration occurs, it vibrates the ground/soil particle with certain velocity and imparts to it certain amount of acceleration. Ground vibrations are, therefore, quantified as displacements that vary with time (in terms of 'mm'), accelerations (in terms of 'g') and/or particle velocities (in terms of mm/s) at particular ground locations [2]. The damage potential also depends upon the predominant frequency besides the PPV. Reference [3] made extensive studies to evaluate the influence of 14 blast variables considered to be having an influence on the amplitude of ground vibrations. They found that charge weight per delay and length of delay to be having the most significant influence on the intensity of ground vibrations. It is very difficult to define the precise level of vibration at which damage begins to occur in a structure. Safe levels for assessing the damage have been defined in terms of Peak Particle Velocity (PPV - mm/s) in different countries. In India, the Directorate General of Mines Safety has given threshold PPVs for different structures based on dominant frequency of the wave form. Standards of DGMS and USBM were used for assigning threshold values of PPV for different structures.

B. Water Borne Shock Waves

In an underwater blast the water is pressurized and displaced due to burning and detonation. A huge amount of energy is released from the blast and this energy moves away from the blast center and spreads in all directions. Reference [4] states that during a blast, in the region beyond the direct effect of thermal and detonation effect, two major impacts are shock waves and the expanding gaseous reaction products. The initial high – intensity shock wave is the most dangerous but it loses its intensity as it moves outward from the source of the explosion. The waves that follow after initial shock waves are less severe. In an underwater explosion initial shock wave is followed by a succession of oscillating bubble pulses. A shock wave is a compression wave that expands radially out from the detonation point of an explosion. At a distance from a

Manuscript received Mar. 25, 2016.

Prof. V. Rama Sastry is with the Department of Mining Engineering, National Institute of Technology Karnataka, Surathkal, Mangalore-575025, INDIA (e-mail: vedala_sastry@ yahoo.co.in).

G. Raghu Chandra is with the National Institute of Technology Karnataka, Surathkal, Mangalore-575025, INDIA (e-mail: raghuchandhraindia.com)

C. Karthik is with the National Institute of Technology Karnataka, Surathkal, Mangalore-575025, INDIA (e-mail: karthikcsaseendran @gmail.com)

detonation, the propagation of the shock wave may be affected by several components including the direct shock wave, the surface-reflected wave, the bottom-reflected wave, and the bottom-transmitted wave. The direct shock wave results in the peak shock pressure (compression) and the reflected wave at the air-water surface produces negative pressure (expansion). For an explosion with the same energy and at the same distance, an underwater blast is much more dangerous to animals than an air blast. Shock wave in air dissipates more rapidly and tends to be reflected at the body surface; in water the blast wave travels through the body and may cause internal injury to gas-filled organs due to impedance differences at the gas-liquid interface. The pressure generated due to underwater blasting depends on many factors like – type of explosive, size of the charge, characteristics of the seabed, location of the explosive charge, water depth, distance from the explosion and degree of submersion of the diver. If divers are present underwater while a UW blast is being conducted, it can cause severe damage to the divers depending upon the distance between diver and blast location. The human body can survive relatively high blast overpressure without experiencing barotrauma. Reference [5] in their study found that a blast overpressure of 5psi (3.45MPa) will rupture eardrums in about 1% of people exposed to it, and a 45psi (31.26MPa) overpressure will cause eardrum rupture in about 99% of all subjects. Also the threshold for lung damage was suggested to be about 15psi (10.34MPa) blast overpressure and 35-45 psi (24.13MPa to 31.0MPa) overpressure was found to cause 1% fatalities, and 55(37.92MPa) to 65 psi (44.8 MPa) overpressure to cause 99% fatalities.

Underwater blasts cause severe effect on the marine life as well. Damage to swim bladder and other gas containing organs have been found to be the main cause for the death of fish and other marine mammals [6]. Reference [7] suggested that negative phase of the pressure wave causing the swim bladder to burst outward was the main reason for the death of fishes due to underwater blasts. Studies have found that the damage to gas contained organ was the main reason for the death of marine mammals as well [8]. The lungs and intestinal tract was the organ most affected in these species. Studies by US Army Corps, New York Division found that phenomenon of “cavitation hat,” observed in blasting of aquatic environment is the major reason for increased mortality in aquatic biota. The negative reflected wave generated by the deflection of the water surface toward the air results in a shallow disc of negative pressure centered over the explosive and there is high potential for overextension of air filled organs in aquatic biota due to the negative pressure associated with the cavitation hat.

III. INVESTIGATIONS

The sea bed of Visakhapatnam Port consists of hard Khondalite rock mass. Method of drilling and blasting for fragmenting and displacing the hard rock mass was proposed to enable the dredging activity. A total area of about 2,50,000m^2 was dredged, from the existing draught of about -8m to -16m, uniformly. As the sea bed consists of hard rock mass, explosive energy was used for breaking the hard sea bed, in order to deploy appropriate dredgers. Fig. 1 shows the plan of the dredging area with structures around.

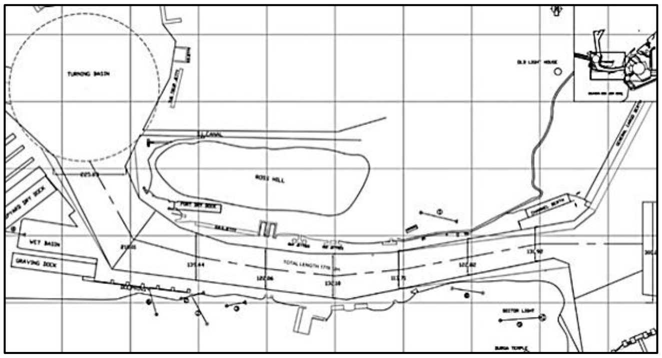


Fig. 1 Entrance channel and turning circle of outer harbor of VPT

A. *Methodology for Under Water Blasting*

The methodology of underwater blasting for rock dredging consisted of the following stages [9]:

a. Pre-Blast survey

- Study bed rock characteristics
- Study structures around to be protected

b. In-Blast monitoring

- Continuous monitoring of ground vibration
- Reengineering blast design
- Creation of data-bank
- Periodic submission of records

c. Post-Blast survey and analysis

- Study of vibration records
- Study of structures around as a part of Post-blast survey

B. *Underwater Blasting*

Method of confined charges was used as the depth to be dredged varied from about -2m to -8m at different places. Based on the rock mass characteristics, it was fixed to use blastholes of 110mm diameter. All the operations of drilling of required number of blastholes, charging of blastholes with required quantity of explosive, establishing the connections in the blast round and final firing of the blast round were carried out from the floating drill barge. The drill barge had facility for mounting required number of DTH drills, compressors, separate storage for explosives and detonators etc. Three drill barges fitted with 15, 12 and 7 drills were deployed. Each barge was mounted with two units of DGPS systems, for ensuring precise positioning of barge. The cycle of underwater blasting operations consisted of the following activities:

- Positioning of drill barge
- Drilling required number of holes
- Simultaneous charging of blastholes, immediately after completion of drilling
- Repeating the above operations for required number of rows
- Establishing the blast layout
- Marching the drill barge to safe distance
- Taking all the precautions
- Firing the blast round

Nitrate based slurry explosive available in couplable plastic tubes was used. Each cartridge was of 1kg and 2kg weights.

Required quantity of explosive to be charged, like 2kg, 3kg, 4kg or 6kg was prepared by coupling the plastic tubes containing explosive. The explosive charge in general varied from 3kg to 8kg per hole as per depth of the blast holes. The maximum permissible charge per delay (determined based on trial blast study initially, for protecting various structures simultaneously) was also considered while determining the charging pattern. Initially, electric short delay detonators, and subsequently shock tube system of initiation was used.

IV. RESULTS AND DISCUSSION

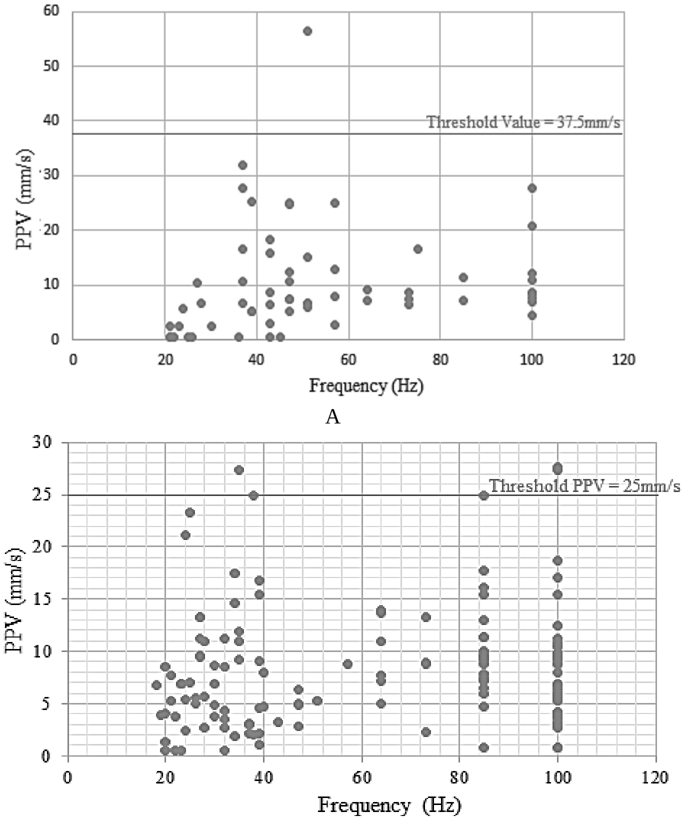
A. *Ground Vibrations*

During the entire period of rock blasting more than 1,345 blasts were conducted and PPVs were monitored at 65 structures, using Blast Vibrations Monitors, Minimate Plus of Instantel, Canada. Some of the structures of importance are shown in Fig. 2. PPVs recorded using Minimate of Instantel, Canada, at Hindustan Shipyard Ferry Jetty and ORS VPT Dry Dock are shown in Fig. 3.

A. HSL Ferry Jetty

B. VPT Dry Dock

Fig. 2 Some important structures



B

Fig. 3 PPVs recorded at different structures

The PPV values for HSL Ferry Jetty varied from <0.51mm/s to 56.5mm/s. Recorded PPV value exceeded the threshold value of 37.5mm/s only in 1.67% cases and it shows the accuracy and efficiency of blast design. For VPT Dry Dock only in 1.43% cases, the threshold PPV value was exceeded. Similarly, for all other 63 structures in the surroundings, the resulting PPV values were well within limits, indicating very safe underwater blasting operations carried out.

B. *Water Borne Pressure Wave and Safe Distances*

As per US Navy guidelines the equation given by [10] is used for calculating the overpressure as:

$$P = \frac{13000\sqrt[3]{W}}{r} \tag{1}$$

where,

P = Pressure on the diver, psi
W = Weight of the explosive (TNT), lb
r = Range of the diver from the explosive, ft

Using the recommended safe exposure values suggested by various standards, reverse calculation was carried out to determine the safe distances using the equation:

$$d_{min} = \frac{13000\sqrt[3]{w}}{P} \tag{2}$$

where,

P = Pressure on the diver, psi
w = Weight of the explosive (TNT), lb
R = Range of the diver from the blast site, ft

According to US Navy guidelines a safe exposure pressure for underwater blasts is considered to be 50psi (34.5MPa) [11]. Using Greenbaum and Hoff equation, calculations were carried out for the frequently used maximum charge per delays (kg) used for the underwater blasting project at the Vishakhapatnam port [1]. Results obtained are depicted in Fig. 4, as it can be used to interpret safe distance for explosive range up to 60kg.

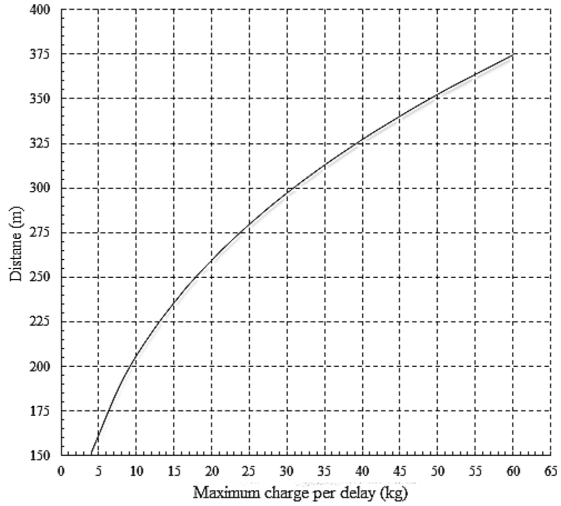


Fig. 4 Safe distance for divers

Reference [12] of the Alaskan Department of Fish and Game's guidelines to protect fish and incubating embryos from the impacts of blasting in and near the water bodies, it is stipulated that blast induced pressures should not exceed 2.7psi (1.9MPa). The Indian Ocean is also home to numerous marine mammals such as dolphins, sharks and porpoise. Studies have shown that blast induced pressures greater than 8psi (5.5MPa) can cause injury to mammals [8]. Accordingly, the safe distances for protecting mammals were determined. The safe distances recommended for fishes, mammals and humans are shown in Fig. 5.

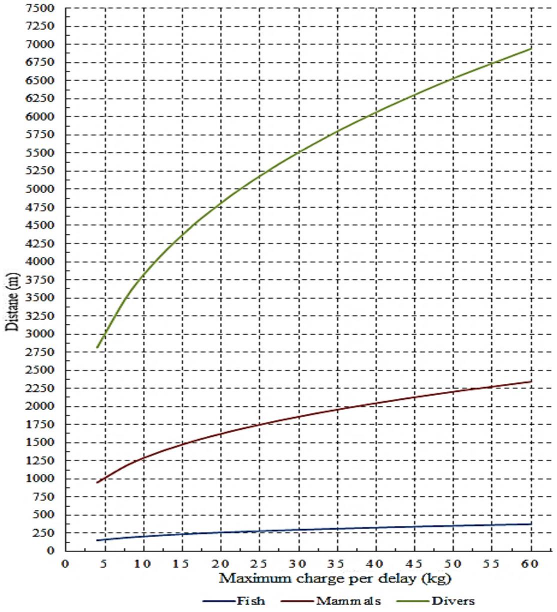


Fig. 5 Combined safety chart for divers, fish and mammals

V. CONCLUSIONS

Underwater blasting is a vital component of rock dredging projects in ports. The major environmental impacts associated with underwater blasting are the water borne shock waves and ground vibration. Use of explosives charge confined in blastholes substantially reduces the effects of ground vibrations on submerged structures and objects in water. Safety criteria recommended in terms of PPV for residential, marine and other structures can be used to monitor and protect them from ground vibrations. Underwater blasting operations were carried out in a safe and efficient manner using down-the-hole delay system, for the first time in the country, by dividing the total explosive column in blastholes into 2 or 3 decks, initiating at different timings, in order to maintain the safe maximum charges per delay for protecting close by structures.

Water borne shock waves are detrimental to the safety of not only the divers, but also to aquatic life like fish and marine mammals.

It is not only important to protect structures, but also the aquatic life from the impact of water borne shock waves from underwater blasts. Various safe distances that can be adopted at site for ensuring safety of divers during underwater blasting were arrived at. For a blast having maximum charge per delay of 20kg in the underwater blast, safe distances were found to be 250m for humans, 1650m for mammals and 4875m for fishes, by considering a threshold pressure value of 1.9MPa for fishes as suggested by Alaskan Department of Fish and Games organization United States. The safe distance values calculated for fishes and marine mammals can be made use in field in other projects also, to ensure that project locations having endangered or rarely existing species can be protected at the time of underwater blasting operations as a part of rock dredging projects.

REFERENCES

[1] V. R. Sastry, "A report on underwater blasting operations for rock dredging in the entrance channel & turning circle of inner harbour of Visakhapatnam Port", An unpublished internal report submitted to Vishakhapatnam Port Trust, India, 2013.

[2] W. I. Duvall, and D. E. Fogelson, *Review of criteria for estimating damage to residences from blasting vibrations*, United States Department of the Interior, pp. 5, 1962.

[3] J. F. Wiss, and P. W. Linehan, *Control of vibration and blast noise from surface coal mining*, USBM OFR, pp. 79–103, 1978.

[4] G. L. Hempen, and T. M. Keevin, *The environmental effects of underwater explosions with methods to mitigate impacts*. US Army Corps of Engineers, St. Louis District, LEGACY Report, pp. 22-25, 1997.

[5] S. Glasstone, and P. J. Dolan, "The effects of nuclear weapons", 3rd ed. *U.S. Department of Defense and the Energy Research and Development Administration*, pp. 552–553, 1997.

[6] D. R. Richmond, J. T. Yelverton, and E. R. Fletcher, *Far-Field Underwater Blast Injuries Produced by Small Charges*, Defence Nuclear Agency, Department of Defence, Washington, D.C. Technical Progress Report, pp. 17–18, 1973.

[7] C. L. Hubbs, and A. B. Rechnitzer, *Report On Experiments Designed to Determine Effects of Underwater Explosions on Fish Life*, California Fish & Game Division. pp. 333–352, 1952.

[8] D. R. Ketten, *Estimates of Blast Injury and Acoustic Trauma Zones for Marine Mammals from Underwater Explosions*, pp. 391 – 407, 1995.

[9] V. R. Sastry, "Underwater blasting for rock dredging for entrance channel and outer harbour circle of VPT", An unpublished report submitted to Visakhapatnam Port Trust, India, 2014.

[10] L. J. Greenbaum, and E. C. Hoff, *A Bibliographic sourcebook of Compressed Air, Diving and Submarine Medicine*, Vol. No.–III, Bureau of Medicine and Surgery, Navy Department, 1966.

[11] Anon, *U.S Navy Diving Manual*, Revision 6, Change A, Published by Direction of Commander, Naval Systems Command, United States Navy, pp. 2.9-2.10, 2011.

[12] K. D. Kristen, and A. M. Catherine, *Blasting Effects on Salmonids*, Alaskan Department of Fish and Game, Division of Habitat, pp. 23, 2013.

Prof. V. Rama Sastry, born on Feb. 16, 1959, obtained his BE degree in Mining Engineering from Osmania University in 1980, and subsequently M.Tech degree in 1983 and Ph.D degree in 1990 in the field of Mining Engineering from Banaras Hindu University, India. His fields of research interests are Rock Mechanics, Rock Fragmentation and Rock Dredging.

Rama Sastry is having teaching and research experience of over 31 years. He is presently working as Professor of Mining Engineering at National Institute of Technology Karnataka, Surathkal, Mangalore (Government of India). He produced 7 Ph.Ds and guiding 6 more scholars in the areas of Rock Mechanics, Tunneling, Underground Large Spaces, Seismic Energy. He guided over 32 PG students projects and over 100 UG projects. He handled 17 R&D Projects and over 165 industry sponsored consultancy projects. He has over 160 research publications to his credit in various conferences and journals.

Prof. Rama Sastry bagged two Gold Medals from The Institution of Engineers (India) and One from Mining, Geological Metallurgical Institute (India) for best paper publication. He served as Director on the Boards of Central Mine Planning & Design Institute Limited (A Govt. of India Public Sector Unit) and KIOCL Limited (A Govt. of India Public Sector Unit).