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Underwater Drilling and Blasting For Hard Rock Dredging In Indian Ports - A Case Study

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Abstract

Underwater drilling and blasting used for rock dredging is associated with several unwanted effects having potential to cause damage to surrounding structures and environment. Though all these ill effects can't be completely eliminated, using controlled blasting they can be minimized to acceptable levels. Underwater drilling and blasting was used for about 25,000 m^3 of hard rock dredging during construction of a Second Liquid Chemical Berth by Mumbai Port Trust (MbPT), Mumbai. The rock formation at the site mainly consists of basalt with compressive strengths varying between 16.04 MPa and 37.96 MPa. The average depth of required excavation was about 2 m. The Elephanta Caves, a World Heritage Site is located about 2.6 km from the proposed site. It was apprehended that ground vibrations resulted from rock blasting may endanger the safety of Elephanta Caves as well as other structures located nearby. Controlled blasting was used to ensure safety of various structures and its efficacy was established by monitoring of blast vibrations on different structures during actual blasting. The use of small quantity of explosives confined in blast holes, non-electrical delay detonators and initiating each hole with a separate delay, helps in minimizing the ground vibration effects on surrounding structures and complete the rock dredging safely in time.

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1. Introduction

The existing facilities of cargo handling in various ports often require expansion for accommodating larger tonnage commercial vessels. Capital dredging constitutes an integral part of most of the construction/ expansion projects in ports. The principal components of dredging are excavation, removal and transport, and disposal of earth material. Underwater drilling and blasting is used very often to accomplish the excavation part of hard rock dredging. However, the site conditions for underwater blasting are always very challenging. The drilling and loading of the blast holes are carried out from specially designed barges or pontoons anchored in deep water. Special kind of explosives and initiating devices are required for underwater blasting, as the explosives are submerged for quite long time and the shock tubes of initiating devices (detonators) are exposed to rough sea conditions for several hours. Due to difficult conditions prevailing during drilling and loading of blast holes, secondary blasting is mostly avoided. Further, underwater drilling and blasting is also associated with several unwanted effects, such as ground vibration, air blasts, shock wave pressure, etc having enough potential to cause damage to the surrounding structures and environment. Though all these effects can't be completely eliminated, using controlled blasting they can be minimized to acceptable levels to avoid damage and accomplish the dredging activities safely. Over the past several years, the Central Water and Power Research Station (CWPRS), Pune has been associated with underwater drilling and blasting used for rock dredging in several major ports in India such as Mumbai Port, Jawaharlal Nehru Port, New Mangalore Port, etc. Based on these experiences and the site specific studies, an appropriate methodology of underwater blasting was evolved to ensure safety of Elephanta Caves, a World Heritage Site against blast vibrations resulted from the hard rock dredging during construction of the Second Liquid Chemical Berth (SLCB) at Pir Pau, off the Mumbai coast for Mumbai Port, Mumbai. The details of these studies are illustrated in the paper.

2. Description of study areas

Mumbai port, on the Arabian Sea is one of the major ports of India handling bulk cargo. The First Chemical Berth (FCB), constructed by the Mumbai Port Trust (MbPT) at Pir Pau, off Mumbai coast, is in operation since December 1996. With a view to meet the increased traffic demand, MbPT Authorities has proposed to construct the SLCB, close to the existing FCB at Pir Pau, Mumbai. The project will involve construction of a 300 m × 63 m berth pocket in front of SLCB, widening and deepening of the existing approach channel and turning circle, which will require about 25,000 m^3 of hard rock dredging by underwater drilling and blasting. The average depth of required excavation was about 2 m and the rock formation mainly consists of basalt with Unconfined Compressive Strength (UCS) varying from 16.04 MPa to 37.96 MPa. The construction site is about 1.8 km away from the Elephanta Island. The world famous Elephanta Caves are located about 800 m inside the Elephanta Island. In addition, the operating FCB and various civil structures in Pir Pau Jetty are also located at about 300 m or more from the blasting sites. Fig. 1 shows the location of various structures around the dredging sites.
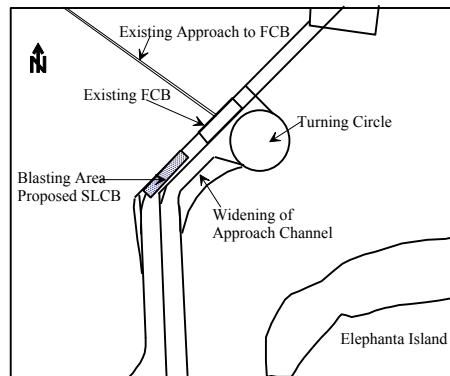

Fig. 1: Location of various structures around the dredging areas.

3. Unwanted effects of underwater blasting

The most undesirable effects associated with underwater blasting are the ground vibrations and underwater shock waves. The ground vibrations have potential to cause structural damage and annoyance to public, while damage to nearby structures/ vessels and marine life may be caused by excessive underwater shock wave pressure. The severity of such unwanted effects mainly depends on the quantity of explosives used, the distance from the blast, the properties of the medium through which the vibration is transmitted, and various blast design parameters. Use of controlled blasting helps to minimize these unwanted effects to acceptable levels.

3.1. Effects of ground vibration

The damage potential of blast vibration is commonly measured in terms of the peak particle velocity (PPV). Besides PPV, the damage potential is also found to depend on the associated predominant frequency. The response of a structure to the blast vibrations depends in a complicated manner on the properties of the ground motion (e.g., amplitudes, frequencies and duration), the characteristics of a structure (e.g., type of construction, importance, condition and dynamic properties) and the type of its foundation. The safety of a structure against blast vibrations can be ensured by adopting controlled blasting. The broad aspects of controlled blasting involves adoption of safe vibration level, developing/ adopting attenuation relations describing the propagation characteristics of blast vibrations, estimating safe charge weights for different distances, designing of blasting patterns and monitoring of blast vibrations during actual blasting operations.

3.2. Safe vibration level

Though it is very difficult to define the precise level of vibration at which damage begins to occur in a structure, various agencies and investigators (Langefors et al., 1958; Duvall and Fogelson, 1962; Nicholls et al., 1971; Siskind et al., 1980; Dowding, 1992; IS 14881, 2001 etc.) have recommended safety criteria in terms of PPV or PPV and associated frequency to ensure safety of structures against blast vibrations. However, protection of historic monuments against blast vibrations posses more complex problems than those in case of commonly encountered residential and engineered structures. Historic buildings are constructed with elaborate exterior and interior ornamentation and artistic details, which can be quite sensitive to low vibration levels. Due to their extended life span, many of the monuments suffer from the effects of gradual ageing and weathering. The vibration levels, which are recommended to ensure safety of structures in good conditions, are non conservative for historical structures. Thus, much more conservative vibration control limits are required to protect historical structures against blast vibrations. To ensure safety of historical structures against blast vibrations with lower predominant frequencies (<10 Hz), several investigators and agencies (DIN-4150, 1984; IS-14881, 2001, Konon and Schuring, 1985; Gupta et al., 1992) have proposed safe vibration levels in the range of 2 mm/s – 6.25 mm/s. The IS Code (IS: 14881-2001) recommends frequency dependent safety criteria for protection of different type of structures against vibrations due to blasting. For safe guarding older homes and historic buildings against construction blasting in urban areas, the code recommended safe PPV of 5 mm/s for frequencies below 10 Hz and 5 mm/s – 30 mm/s for the frequency range of 10 Hz –100 Hz. For engineered structures, the code recommends safe PPV of 25 mm/s for frequencies below 40 Hz and 25 mm/s –75 mm/s in the frequency range of 40 Hz –100 Hz.

3.3. Site-specific safe vibration levels

The Elephanta Caves are a network of sculpted caves having magnificent architectural values and great archeological importance. The Caves are recognized by the United Nations Educational, Scientific and Cultural Organizations (UNESCO) as a World Heritage Site. A highly conservative vibration level of 1 mm/s was adopted as safe vibration level to ensure safety of these Caves against vibrations resulted from the present underwater rock blasting. In addition to Elephanta Caves, various civil structures located in the existing berths are also required to be safeguarded against blast vibrations. The nearest distance between these structures and the blasting site is more than 300 m. The structures in the existing berth are massive engineered structures and are able to withstand higher PPV

levels compared to historical structures. As recommended by IS-14881 (2001), PPV between 25 mm/s to 75 mm/s are considered safe for engineered structures. Various structures located at the existing berth at Pir Pau can withstand these vibration levels without producing any kind of damage. However, as a conservative approach, a PPV of 10 mm/s in all frequency range was adopted as safe PPV to ensure safety of various structures on existing berth. The adopted safe PPV levels along with the safe vibration levels recommended by IS-14881 (2001) are shown in Fig. 2.
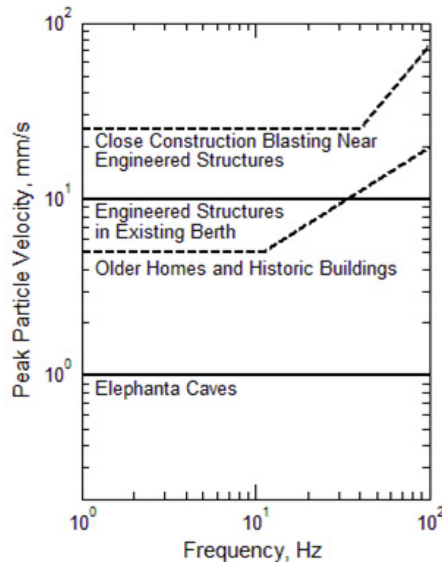

Fig. 2: Site-specific safety criteria (modified after IS-14881, 2001).

3.4. Prediction of ground vibration

The amplitudes and frequencies of the elastic waves generated from blasting attenuate with distance. The rate of attenuation is faster in the initial stages of travel and comparatively slow as distance increases. The attenuation also depends on several other parameters such as density of rock, presence of joints in the rock, degree of saturation of various layers, etc. As the effects of all these parameters cannot be defined accurately in an analytical model, the attenuation of blast vibration for a site is commonly studied by developing an empirical relation using ground vibration data recorded at the actual site or other sites having similar rock type. Several empirical relationships have been suggested by different investigators (Ambrasey and Hendron, 1968; Siskind et al., 1980, Ghosh and Daemen, 1985, Tripathy and Gupta, 2002, etc.) to describe the attenuation characteristics of blast vibration. However, the following form of empirical relationship is used most widely to study the attenuation of blast vibration:

$$V = K\left(\frac{R}{\sqrt{Q}}\right)^{\beta} \qquad (1)$$

Where, *V* is the peak particle velocity (mm/ s), *R* is the distance (m) between the observation and blast points and Q is the charge weight (kg) per delay. The factor $R/\sqrt{Q}$ is commonly called as square-root scaled distance (SSD). *K,* and β are constants, site-specific parameters, which are evaluated by regression analysis of the observed ground vibration data. The values of constants *K* and β are evaluated for a particular site by detonating a few experimental blasts with different charge weights Q and recording the   ground vibration at different distances (R). However, many times it is not possible to carry out experimental blast studies needed for this purpose at the actual site of excavation. In such situation, attenuation relation developed from blast data collected from site with similar geological set up are used to estimate the preliminary safe charge weight for different distances. With a view to

estimate the safe quantity of charge weight per delay for the present study, the following attenuation relation with 95 % confidence level developed from blast vibration data recorded at Elephanta Caves during underwater blasting at Nhava Sheva Port (having similar geology as of the present work) has been used (Technical Report No. 2997, 1988).

$$V(0.95) = 745\left(\frac{R}{Q^{0.5}}\right)^{-1.43} \tag{2}$$

Using *V* as 1 mm/s and R as 1800 m in Eqn. (2), the charge weight per delay is estimated to be 311 kg. Similarly for *V* as 10 mm/s and R as 300 m, the charge weight per delay is found to be 216 kg. Thus, the minimum of the two, a charge weight of 216 kg per delay can be safely used without exceeding the safe vibration levels of 10 mm/s at Pir Pau Jetty and 1 mm/s at Elephanta Caves.

3.5. Effects of shock waves

The shock wave pressure resulting from underwater blasting can cause damage to submerged structures, objects and vessels. The effects of underwater shock wave on objects can be estimated in terms of the primary peak pressure P_m. The pressure due to explosives detonated underwater can be estimated using the following relationship (Cole, 1948):

$$P_m = 52355\left(\frac{R}{Q^{0.33}}\right)^{-1.13} \tag{3}$$

Where P_m is pressure in kPa, R is distance in m and Q is charge weight per delay in kg. This relation is based on shock waves from underwater explosion with surface charges, and thus predicts higher amplitude shock waves than that with explosive charges confined in blast holes. Nedwell and Thandavmoorthy (1992) compared the pressure time histories from detonation of small charges in open water and those in bore holes and found that the peak pressure from explosive charge confined in boreholes was only 6 % of the pressure resulting from same size of charge detonated in water at the same distance. Hempen et al. (2005) compared pressure from four confined shots with computed open water pressures, and found that the confined pressures are 19 % to 41 % of open water pressure. Such a large-scale reduction in shock wave pressure is probably due to the fact that more of explosive energy is consumed in rock fragmentation and displacement. The water borne shock wave pressure is reduced with increasing distance from the blast. In addition to distance, the pressure is also significantly affected by other factors, such as charge weight per delay, the depth of water, blast geometry, etc. Use of explosive charges confined in boreholes significantly control the adverse effects of shock wave pressure on submerged structures, objects and vessels during rock dredging by underwater blasting. The maximum distance R_{max} for which underwater blasts induce damages by shock waves to different types of submerged objects can be computed from the following relation (Raadit, 1980):

$$R_{max} = 1.5Q^{0.333} \tag{4}$$

The safe distance (R_0) for underwater blast should be much more than R_{max} and it can be defined as:

$$R_0 = SF \times R_{max} = SF \times 1.5Q^{0.333} \tag{5}$$

Where *SF*, safety factor greater than 1 and the numerical value of *SF* is to be of an order, wherein no damage is experienced. The safety of different objects such as hydraulic structures or vessels against shock wave pressure due

to underwater blasting can be ensured by adopting safety factor (*SF)* varying from 2 to 18 Raadit (1980). Using *SF* as 18 and *Q* as 216 kg (evaluated in section 3.4) in Eqn. (5), the safe distances during underwater blasting is estimated to be 162 m.

4. Underwater drilling and blasting

The drilling of blast holes for underwater blasting is carried out with drilling rigs mounted on pontoon or barge. Initially, the required position of drilling is finalized using various positioning systems operated from the barge. The drilling barge is brought into the predetermined location to drill a line of holes and is held in position by anchoring. The drilling towers are positioned over the specified drill hole location and drilling commences. The most commonly used drilling method for underwater blasting is called Over Burden Drilling (OD). In this method of drilling, a casing pipe is driven separately into the rock through the overburden for a distance sufficient to provide a seal to prevent small stones, sand, or silt from filling the drill hole. After the casing pipe is fixed, the inner drill rods are inserted through the casing pipe and the shot hole is drilled to the required depth. Upon reaching the required depth, drill rod is retrieved and the hole is ready for charging with explosives. In underwater blasting usually number of holes are drilled in a line and after completion of drilling and loading of all the holes in the line, the barge is shifted to the next position for drilling and charging of another row of holes and the operation is repeated until required number of holes has been completed for a particular blast. For drilling of blast holes at MbPT site, the entire blasting area was divided into 21 different blocks and each block was subdivided with rectangular grid of 1.5 m × 2.8 m. At each grid point, 150 mm diameter holes with 1.5 m burden and 2.8 m spacing were drilled to the required depth. Truck mounted hydraulic down-the-hole (DTH) drilling machine was used for drilling of blast holes.

4.1. Explosives and initiating devices

The explosives used for underwater blasting should have very good water resistant properties as it has to remain underwater for several hours. Now-a-days, slurry and emulsion explosives primed with non-electric (NONEL) delay detonators are commonly used. In order to ensure the reliability of detonation, two detonators are normally used in each hole. KELVEX-P, Couplable Plastic Tube (CPT) available with 125 mm diameter cartridge of 6.25 kg each was used as explosives for blasting the holes in this study. Each hole was loaded with only one or two cartridges of explosives. The CPT explosive cartridge was primed with 25 m long non-electric shock tube initiation (NONEL) system provided with delay detonators. In the present blasting at MbPT, 200 ms in-hole delay, 17 ms delays between holes in the same row and 25 ms delays between two rows were used. A typical blasting pattern with 12.5 kg charge per delay used at site is shown in Fig. 3.
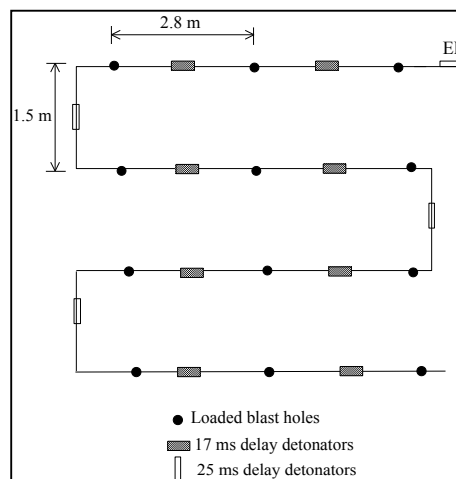

Fig. 3: Typical blasting pattern used for underwater blasting

5. Monitoring of blast vibrations

Four units of three component engineering seismograph (Model DS-077 from M/s Instantel Inc., Canada and Mini Super graph from M/s NOMIS Seismographs, USA) were used for monitoring of vibrations. The vibration time histories are recorded digitally on these instruments and retrieved using a Personal Computer. During the entire period of rock dredging, 36 blasts were conducted and each blast was monitored at Elephanta Caves as well as at different structures such as marine dolphin, pump house, fire station located at the existing Pir Pau Jetty. The vibration levels recorded at different structures on Pir Pau jetty varies between 0.96 mm/s and 2.98 mm/s. Fig. 4, shows the distribution of PPV levels observed on different structures in Pir Pau jetty. However, the seismographs located at the Elephanta Caves could not record any of the blast vibrations indicating that the vibration levels are less than the trigger level of the seismograph. Seismographs used for blast vibration measurements are commonly provided with trigger mechanism, as a result the instruments automatically initiate recording only after the trigger level is exceeded. At Elephanta Caves, the trigger level for the instruments were set at 0.25 mm/s and none of the seismographs was triggered during the entire period of monitoring. Non-triggering of seismographs at Elephanta Caves indicates that the explosive charge used in blasting was not sufficient to produce vibrations exceeding the level of 0.25 mm/s at the monitoring locations.
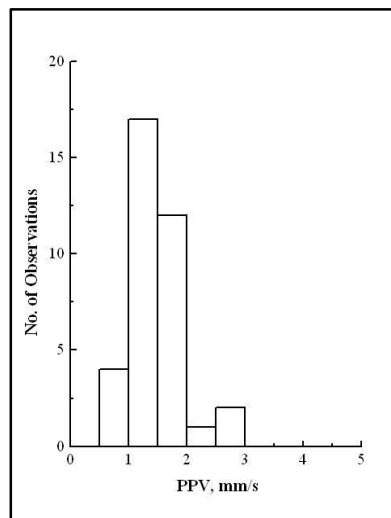

Fig. 4: Distribution of PPV observed on different structures on Pir Pau jetty.

6. Conclusions

The two important environmental effects of blasting; viz., ground vibration and water borne shock wave pressure are of major concern while using underwater drilling and blasting for hard rock dredging. Use of explosives charge confined in boreholes substantially reduces the effects of shock waves on submerged structures and objects in water. Safety criteria recommended in terms of PPV for residential structures or engineered structures cannot be applied for world heritage structures. Due to the closeness of the operating chemical berth and world heritage sites, highly conservative vibration limits were adopted and all the blasts were monitored during the entire period of rock blasting. Blasts were carried out using much lower charge weight per delay than allowable to minimize the impact of ground vibrations on various structures around construction sites. The use of required quantity of explosives confined in blast holes, non-electrical delay detonators and initiating each hole with a separate delay, helps in minimizing the unwanted effects of underwater rock blasting on surrounding environment and complete the work safely in time.

Acknowledgements

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