Distance of structure causes amplification or reduction in vibration magnitude with an increase in height of measurement

Seismic energy generated due to detonation of explosive causes environmental degradation and give rise to socio-environmental complaints. Based on frequency of vibration and amplification in vibration magnitude with an increase in height of measurement on a structure, vibration magnitude i.e., ppv, measured near the foundation of structure has been considered as the main parameter for safety of structures. The paper, here, discusses about anomaly to general observation i.e., instead of amplification, reduction in ppv with an increase in height of measurement on a structure. The paper, with the help of vector analyses has also attempted to justify that distance of structure from the place of blasting, magnitude of each component and the component triggering the structure of vibration plays an important role for such occurrence. The paper communicates that when longitudinal wave component triggers the structure to vibrate, amplification in vibration magnitude is observed with an increase in height of measurement. On the contrary, when vertical or transverse component triggers the structure to vibrate, attenuation in vibration magnitude is observed with an increase in height of measurement. The paper, lastly, communicates that in addition to limiting vibration magnitude for safety of structures, quantum of energy transmitted to the structure in accordance with strength properties of the structure should be analyzed to ascertain safe vibration limit for structures.

Introduction

Ever-increasing excavation work in close proximity to dwellings and concern of local inhabitants for socio-environmental impacts lead to confrontation and even litigation between excavation management group and local people. Noise, fumes and dust, though, a severe concern for environmental degradation, the significant impacts of blasting that give rise to complaints are air-overpressure and blast-induced ground vibration (Mandal et al, 2007; Oriad, 1999; 2002; Siskind et al, 1986 a, b; Mandal et al, 1997; Raina et al, 2002). Characteristics of blast-induced vibration wave varies with rock mass characteristics, blast design parameters and type of blasting viz., tunnel blasting, deep hole blasting by large and small diameter explosives and deep-cut blasting for dragline benches (Sun, 2003). Vibration magnitude that impart damage to structure depends upon properties of construction material, thickness of walls, depth and width of foundation and dimension of structure with respect to source of blasting (Mandal et al, 2005, a, b). Response of structure to blast vibration depends upon duration, amplitude and frequency of vibration and quantum of energy transmitted to structure (Mandal et al, 2007). The paper, here, deals with measurements of blast-induced vibration that were carried out in different floors of a two storied office building. When the structure was very close to the blasting site i.e., well within 50 m from the blasting site, vibration was monitored on the structure. An anomaly was observed in the measurement i.e., instead of amplification in vibration magnitude, reduction in vibration magnitude was observed with an increase in height of measurement. The author with the help of vector analyses have attempted to explain the cause of such occurrence. The paper, thereafter, communicates that since vibration is a form of energy transmitted through the medium or to the structure during blasting, wave characteristics and magnitude of energy transmitted to the structure should also be evaluated to limit safe vibration magnitude. Energy in terms of peak hold, cumulative and magnitude of strain and its energy transmitted to structure should be evaluated.

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Safety standards for structures

Damage identification for structures can be carried out by either vibration based damage identification method or through visual inspection or with the help of experimental tests like acoustic or ultrasonic methods, magnetic field methods, radiography, eddy-current method and thermal field method (Chang, 2003; Doherty, 1987; Worden, 2004). The first two methods do not provide accurate information about the extent of damage but can alert its presence. Experimental tests, on the other hand, can estimate the extent of damage in an accurate way. In addition to blast-induced damage, deterioration in structures may also take place due to various environmental forces such as precipitation, daily and seasonal changes in temperature, changes of building material properties under the influence of moisture and drying, wind speed and direction, soil condition and soil behaviour under structural loading and human activities.

Seismic energy is about 7% of the total energy of heat of explosion. For same distance of concern and same charge per delay, magnitude and characteristics of vibration varies with blast design parameters viz., total charge, charge per hole, charge distribution, charge diameter and blast geometry (Mandal et al, 2006). To have safe blasting practice various countries have stipulated safe vibration level for safety of structures (DIN standard, 1986; Indian standard, 1973; DGMS standard, 1997; Morris, 1950; Habberjam and Whetton, 1952; Crandell, 1949; Medearis, 1977; Siskind et al, 1980; Dowding, 1981, 2000; Duvall and Fogelson, 1962; Wiss, 1968; Nicholas, 1971; British standard BS7385 and USBM's (OSM's) criteria Oriard, 1999; Quesne, 2001). Several empirical equations were also formulated to determine attenuation characteristics and predict vibration magnitude for any distance of concern (Palroy, 1991; Ghosh and Damen, 1983; Redpath and Ricketts, 1987; Siskind et al, 2000). Investigation carried out by Davidsavor, et al, 2003 communicated that no significant evidence of crack was observed for peak particle velocity ranging from 112 mm/s to 217 mm/s with an average intensity of 170 mm/s. Hajduk et al, 2004 communicated that settlement of ground due to loose soil and densification of ground due to impact of blasting plays an important role in quantifying vibration level for safety of structures. Bay, 2003 communicated that safe vibration magnitude of 12.7 mm/s, proposed by Chae, 1978, should be appropriate for historic buildings and structures having safe level of 12.7 mm/s should not be suitable for residential purpose. Svinkin et al, 2000, a,b communicated that to predict the impact of blast-induced vibration on structures, impulse response function prediction (IRFP) method should be implemented. The findings communicated that existing background vibration status and its sources are important to obtain information regarding blast-induced impact on the structures. Recent researchers communicate that damage to structure depends upon quantum of energy transferred to structure and structural response to blasting should be evaluated prior to limiting the damage level of vibration magnitude (Langan, 1980; Qian, S. et al, 2002; Zhang, Y., et al, 2002).

Masonry structure

Masonry structure is an assembly of regular shaped high strength units (bricks) bounded together with a binding material (mortar) between them. For good construction, mortar must be strong, durable and capable in keeping the structure in intact condition by creating a water resistance barrier. The nonelastic, nonhomogeneous and ansiotropic masonry wall composed of two different property materials viz., brick and mortar, is typical in behaviour under load. The sustaining capacity of flexural load on masonry wall in perpendicular direction to bed joints being two to five times larger than that observed in parallel direction to bed joints, the masonry walls are weak in tension, in-elastic in nature even for small distortion under lateral load and can sustain high magnitude of compressive force (McNary and Abrams, 1985; Atkinson and Noland, 1983; Drysdale et al, 1994; Hemant et al, 2007; Doebling et al, 1996). For non-load bearing walls, flexural strength of masonry is limited by its tensile strength and shows a brittle behaviour due to its low strength (BIA Technical Reports, 8 & 15; ASTM C 270-02; Wood, S. L., 1995; Wrights, B. T. et al, 1993; Davidsavor et al, 2003). Strength of masonry wall and its stiffness lies between strength properties of brick and cement and varies with bond strength of hardened mortar, mortar thickness, brick texture, suction power of brick, air content, flow characteristics of mortar and curing time (Dayaratnam, 1987; Sarangapani et al, 2002, 2005). Mortar having high water content ratio looses water when comes in contact with absorbent units (bricks) and enhances the bond strength between the units. Too high or too low IRA is detrimental for good initial and final bond strength between brick and mortar and affects masonry flexural strength, water tightness and durability (Drysdale et al, 1994). The flexural bond strength of mortar cement varies between 0.8 and 70 MPa. Test results for a particular type of brick indicates that for load varying between 16.1 and 28.9 MPa and modulus of elasticity between 500 and 7500 MPa, the failure strain varied between 0.0057 and 0.0072 (Kaushik et al, 2007). For masonry structures, since, differential deformation strength is governed by the bond strength (mortar strength) between two units (bricks), different types of tensional failure modes should be analyzed for both joints and units. Aimone-Martin et al, 2005 communicated that to assess the possibility of cosmetic cracks or massive failure, magnitude of induced strain in the structural components should be determined in terms of difference in displacements at different floors, structural motions in the perpendicular direction to the plane of wall (hade joint) and global shear strain on the structure. According to Dowding, 1985 failure strain magnitude for gypsum core of drywall varied between 300 and 500 micro-strains and that for bricks between 700 and 1000 micro-strains. Hade joints, mitigated by staggered units laid in running bond have larger shear stress than bed joints. Strength of masonry is also governed by coefficient of friction between mortar and brick and uni-axial compressive strength in both perpendicular and parallel direction to bed joints.

PCC structures have brittle failure characteristics and fails with the initiation of crack (Paulay, et al, 1992). Reinforced concrete (RCC), on the other hand, can sustain more deflection and possess more flexural strength. Strength properties of reinforced concrete depend upon quality and density of reinforced material (Priestley, et al, 2000). Strength properties of RCC increase with an increase in reinforced material and strength varies with diameter and spacing of reinforced material (Ombers et al, 2000; Aiello and Ombers, 2000).

Blast wave characteristics and energy evaluation

Vibration magnitude is the resultant impact of external energy transmitted to the sensor during its propagation. In blasting, the resultant impact is due to detachment of material from its in-situ condition, throw of blasted fragments and time in retaining gaseous energy within blast hole i.e., time elapsed between detonation of explosive and its release to general atmosphere or work done by explosive in fragmenting and dismantling rock mass from its in-situ condition. Furthermore, since, seismographs record wave characteristics of particle motion at the location of sensor, vibration recorded by any seismograph may be defined as the energy transmitted to the particle at the location of sensor during propagation of blast-induced vibration wave.

Blast-induced vibration wave, mainly comprising body and surface waves is, therefore, a form of energy transmitted to the surroundings after detonation of explosive within a blast hole. The wave signature, recorded by seismographs indicates magnitude of energy transmitted to the sensor at the place of measurement. Since, peak magnitude of any wave signature possesses maximum energy, the characteristics of wave in terms of acceleration, deceleration, duration of peak and wave length should be determined from the peak, Fig.1. The different magnitudes of wave characteristics from its peak can be determined with the help of equations 1 to 4. Schematic diagram of blast wave signature, generated during blasting, is shown in Fig.2. With the help of blast wave analysis software, magnitude of vibration along Y-axis and the corresponding time recorded along X-axis can be noted manually. Thereafter, with the help of the equations 5-7, magnitude of energy transmitted to the structure in the form of total energy, peak hold energy and cumulative peak hold energy can be evaluated. At each infinitesimal time interval, magnitude of vibration being the maximum displacement or amplitude, magnitudes of maximum displacement and relative displacement during propagation of blast wave can be determined with the help of equations 8 & 9 respectively. Magnitude of strain and its energy can be evaluated from displacement magnitude obtained from wave signatures. In Fig.2, the perpendicular lines AB and CD represent magnitude of vibration vis-à-vis magnitude of displacement at time A & C respectively. Magnitude of strain, defined as the ratio between change in displacement and original displacement, can be evaluated. Similarly, magnitude of strain energy can be evaluated as the ratio between the area of the triangle BED and the area of trapezium ACDB. Magnitude of strain and corresponding energy generated due to strain can be determined with the help of equations 10 and 11 respectively. Considering structural dynamics, magnitude of bending moment or stress developed due to bending can also be evaluated with the help of equation 12. Since, structural behaviour due to impact of blasting is dynamic in nature, maximum allowable deflection or bending can be ascertained after laboratory determination of maximum dynamic stress that can be sustained during oscillation of the structure.

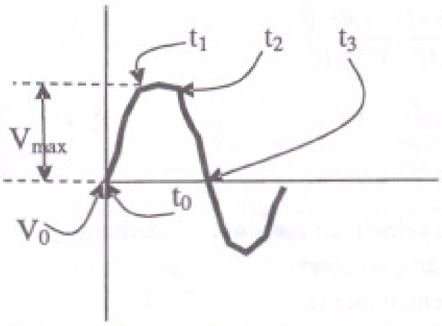

Fig.1 Schematic diagram of peak for a wave signature

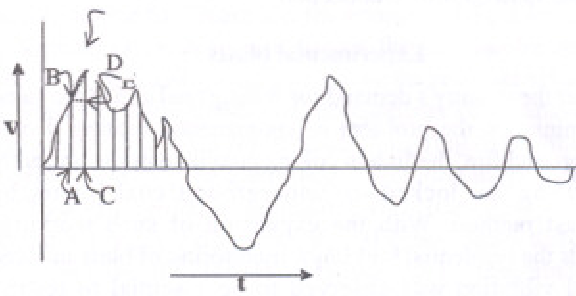

Fig.2 Schematic diagram of waveform for analysis of transmitted energy

$$Wavelength = 2c(T_3 - T_0) \quad ... (1)$$

$$Duration\ of\ peak = (T_2 - T_1) \quad ... (2)$$

$$Acceleration = (V_{max} - V_0) \div (T_1 - T_0) \quad ... (3)$$

$$Deceleration = (V_{max} - V_0) \div (T_2 - T_3) \quad ... (4)$$

$$Work\ done = m_i \sum_{i=2}^{i=n-1} \left[\left(V_{inst(i)} + V_{inst(i-1)}\right) \times \left(T_i - T_{(i-1)}\right)\right] \div 2 \quad ... (5)$$

$$Peak\ energy = V_{phi}\left(t_{(i+1)} - t_i\right) \quad ... (6)$$

$$Cumulative\ energy\ for\ peak\ holds = m_i \sum_{i=1}^{n} V_{ph(i)}\left(t_{(i+1)} - t_i\right) V_{phi}\left(t_{(i+1)} - t_i\right) \quad ... (7)$$

$$Maximum\ displacement\ or\ amplitude\ (t_i) = V_{inst(i)} \quad (8)$$

$$Relative\ displacement\ (amplitude)(i) = V_{inst(i)} - V_{inst(i-1)} \quad ... (9)$$

$$Strain = \left(V_{inst(i)} - V_{(i-1)}\right) \div V_{inst(i-1)} \quad ... (10)$$

$$Strain\ energy = \frac{Area\ of\ triangle\ BDE}{Area\ of\ trapezium\ ACDB} =$$

$$\frac{0.5*DE*BE}{0.5(AB+CD)AC} \quad \text{... (11)}$$

$$\frac{M}{I}=\frac{f}{y} \quad \text{... (12)}$$

where,

c = sonic velocity of transmitting medium

M = bending moment

I = moment of inertia

f = stress developed due to bending

y = maximum allowable deflection

Experimental blasts

To meet the country's demand for coking coal and at the same time minimize the problem of spontaneous heating due to underground fire, the Indian coking coal industry is presently excavating the locked up underground coal pillars by opencast method. With the expansion of such workings towards the residential buildings, monitoring of blast-induced ground vibration was observed to be essential to restrict maximum allowable charge per delay to be fired in a round for safety of the structures. During such investigation, vibration for two blasts was also monitored in different floors of an old two storied office building, located well within 50 m from the blasting site. In each blast vibration was monitored at three locations viz., ground (near foundation of structure), roof of first and second floor. The three dimensional view and plan view of the structure is shown in Figs.3 and 4 respectively. Since, sensors were located very close to the blasting site and on smooth surface at different floors, possibility of rattling of sensors was nullified by placing one sand bag, each weighing about 25 kg, on each sensor. The details of the blasts along with vibration measured are given in Table 1.

Fig.3 Office building where measurement of vibration was carried out

Analysis of measured magnitude

For surface blasting and surface measurement amplification in vibration magnitude is generally observed with an increase in height of measurement on a structure. On the contrary, for underground blasting and surface measurement, reduction in

TABLE 1: BLAST DETAILS AND MEASURED VIBRATION MAGNITUDE AT GROUND AND DIFFERENT FLOORS OF A STRUCTURE

Parameters	1st Blast						2nd Blast								
Depth of hole (m)	6						6								
Charge per hole (kg)	31.25						31.25								
Maximum charge per delay (kg)	62.5						62.5								
Total charge (kg)	375						468.75								
Initiation system	NONEL						NONEL								
	Ground			Floor of 1st Floor			Ground			Floor of 1st Floor			Floor of 2nd Floor		
Horizontal distance (m)	35			35			15			15			15		
Peak particle velocity (mm/s)	16.1			15.2			71.3			18.4			8.89		
	Trans	Vert.	Long	Trans	Vert.	Long	Trans	Vert.	Long	Trans	Vert.	Long	Trans	Vert.	Long
Particle velocity (mm/s)	8.13	14.2	13	4.19	8.7	13.5	48.4	59.9	43.7	14.7	7.11	12.2	4.06	6.35	7.87
Frequency (Hz)	24	32	23	28	32	19	34	32	24	43	73	16	22	11	8
Triggering time (ms)	0.086	0.197	0.089	0.101	0.072	0.095	0.077	0.098	0.081	0.066	0.023	0.068	0.146	0.193	0.26
Peak acceleration	0.119	0.318	0.199	0.928	0.186	0.172	1.38	4.08	0.848	0.504	0.398	0.292	0.0795	0.119	0.0663

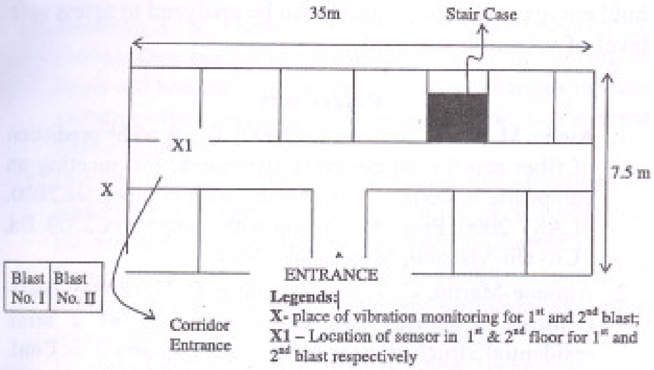

Fig.4 Plan view of structure under investigation

measured vibration magnitude is observed with an increase in height of measurement on a structure. However, an anomaly to general observation may be noticed when structure is either very close to the blasting site for surface blasting or when the radial distance between the structure and blasting site is substantially higher than the vertical cover. For surface blasting and surface measurement, two such measurements were recorded. In both the blasts, vibration was monitored with seismographs of Instantel make. The instruments were placed at ground surface, near foundation of structure and in the roof of first and second floor. In these blasts, instead of amplification, reduction in measured magnitude of vibration was observed with an increase in height of measurement on the structure. Considering this anomaly and reviewing into the theoretical work of Wu, C., Hao, H. and Lu, Y., 2005, vector analysis was carried out to justify the cause of such occurrence.

For analysis, a minimum of two paths for transmission of blast wave from source 'O' to structure 'C' has been considered viz., along paths 'OC' and 'OBC' (Fig. 5). For path along 'OC', wave will transmit through rock medium and will be body wave. However, for path along 'OBC', the transmitted wave will be a combination of body wave (from O to B) and surface wave (from B to C). Distance travelled by blast wave through rock medium to locations 'B' and 'C' can be determined with the help of equations 13 and 14 respectively.

$$SL_1 = \sqrt{\left(H^2 + L_1^2\right)} \quad \text{... (13)}$$

$$SL_2 = \sqrt{\left[H^2 + (L_1 + L_2)^2\right]} \quad \text{... (14)}$$

If velocity of body wave i.e., wave through rock medium is V_m, then time taken by the wave to reach 'B' and 'C' will be $T_1 = SL_1/V_m$ and $T_2 = SL_2/V_m$ respectively. For path along 'OBC' the wave had to travel from 'B' to 'C' as surface wave to vibrate the structure. If V_s is the velocity of surface wave, then total time taken by blast wave along the path 'OBC' to reach the structure will be $T_{11} = T_1 + L_2/V_s$. Now, if T_{11} is less

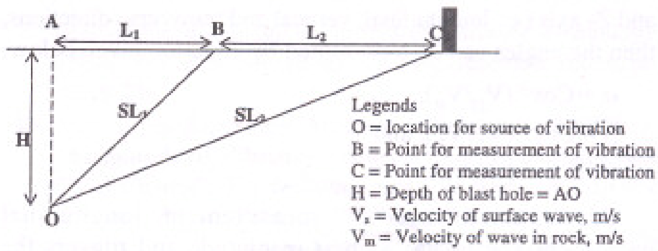

Fig.5 Schematic diagram showing vibration propagation with respect to structure

than T_2 then longitudinal wave component will trigger the structure/sensor to vibrate. On the contrary, if T_2 is less than T_{11}, vertical component will trigger the structure/sensor to vibrate. For path along OBC, let V_{11} be the resultant vibration magnitude for three orthogonal components viz., transverse, V_{11T}, longitudinal, V_{11L}, and vertical, V_{11V} (Fig.6a). Similarly, for path OC, let V_{12} be the resultant vibration magnitude for the three orthogonal components viz., transverse, V_{12T},, longitudinal, V_{12L}, and vertical, V_{12V} (Fig.6b). Since, direction and magnitude of resultant is influenced by magnitude of three orthogonal components; magnitude of each component is an important parameter to assess the characteristics of vibration with an increase in height of structure. If longitudinal component has highest magnitude, the resultant will be sub-horizontal and will act as moment at ground level for structure to vibrate. This will cause amplification in vibration magnitude with an increase in height of measurement. However, if vertical component has highest magnitude, the direction of resultant will be sub-vertical and will transmit through structural medium and act as body wave. Furthermore, brick and mortar construction having intermittent layers of brick and mortar, the refracted wave from mortar to brick will be towards the normal and will transmit through the brick wall. During such transmission, energy of blast wave will also get reduced due to the resistive force offered by brick and mortar particles/medium to the path of transmission and reduction in vibration magnitude will be observed with an increase in height of measurement. If α, β and γ are the angles the resultant is subtending with X-, Y-

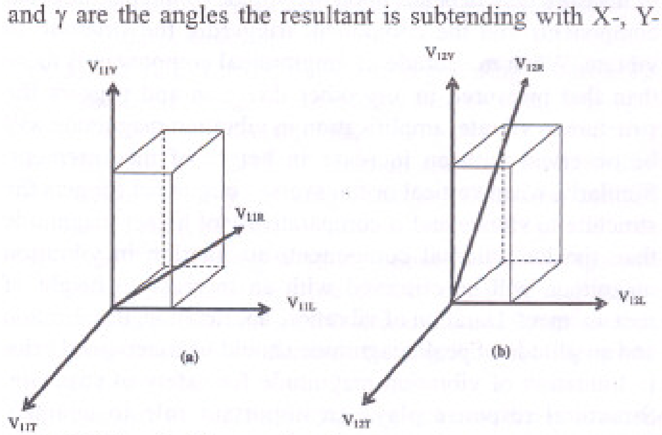

Fig.6 Schematic diagram showing the resultant vector for three orthogonal vectors

and Z- axis i.e., longitudinal, vertical and transverse directions, then the angles can be represented by equation given below:

$\alpha = Cos^{-1} (V_H/V_R)$,

$\beta = Cos^{-1} (V_V/V_R)$, and

$\gamma = Cos^{-1} (V_T/V_R)$

For longer distances of measurement, longitudinal component always has highest magnitude and triggers the structure to vibrate and therefore, amplification in vibration magnitude is recorded with an increase in height of measurement on a structure. This force when strikes the wall acts as a moment and allows the wall to deflect like a cantilever beam rigidly supported at one end. The force acting near the foundation of the wall rigidly supported at base will amplify the vibration magnitude with an increase in height of measurement. For structure having high L/W ratio, where, L is the dimension of structure along longitudinal wave propagation direction and W is the dimension perpendicular to it, attenuation of vibration magnitude may be observed with an increase in the height of measurement. Similar characteristic of amplification or reduction in vibration magnitude may be observed for underground blasting and surface measurements. When the structure is vertically above the blasting site and/or comparatively high magnitude of vertical component triggers the sensor to vibrate, reduction of vibration magnitude will be observed with an increase in height of measurement. However, when structure is at some horizontal distance from vertically above the location of underground blasting (radial distance is comparatively higher than vertical cover), horizontal component of particle velocity triggers the structure to vibrate and amplification in vibration magnitude will be observed with an increase in height of measurement.

Conclusion

Magnitude of vibration cannot be the single parameter to assess safety of mortar and brick structures. Amplification or reduction of vibration magnitude with an increase in height of measurement depends upon magnitude of three orthogonal components and the component triggering the structure to vibrate. When magnitude of longitudinal component is more than that measured in any other direction and triggers the structure to vibrate, amplification in vibration magnitude will be observed with an increase in height of measurement. Similarly, when vertical or transverse component triggers the structure to vibrate and is comparatively of higher magnitude than the longitudinal component, attenuation in vibration magnitude will be observed with an increase in height of measurement. Duration of vibration, acceleration, deceleration and amplitude of peak magnitude should be ascertained prior to limitation of vibration magnitude for safety of structure. Structural response plays an important role to quantify vibration-induced damage level. Characteristics of vibration energies transmitted to structure in terms of total energy, peak hold energy and strain should also be analyzed to assess safe level of vibration standard.

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