Particle Velocity of Ground Vibration Reflects Mechanism of Rock Breakage and Damage to Structures

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***Abstract*- Magnitude of particle velocity of each orthogonal component and the component triggering the sensor to monitor depends upon blast geometry and location of measurement with respect to source of vibration. Considering experimental investigations carried out at four different sites, the paper communicates that wide blast geometry (burden and spacing) with respect to depth of blastholes and location of measurement i.e., measurements made at higher altitudes (greater vertical distances) with respect to horizontal distance from vibrating source will result into higher magnitude of vertical or transverse components and will also trigger the sensor to monitor. Similarly, when measurements are made at same altitudes, vertical or transverse component will trigger the sensor to monitor when placed at closer distances and longitudinal component will trigger the sensor when placed at far off distances. The paper lastly communicates that since, each orthogonal vibration component behaves indifferently to cause structural damage, magnitude of each orthogonal component and the component triggering the structure plays an important role to ascertain safety of structure. Longitudinal component in comparison to vertical or transverse component generates more stress on structures and is more susceptible to cause damage to structures.**

Keywords*- *P-wave Velocity; Blast Geometry; Distance of Measurement; Structural Stability

I. INTRODUCTION

Detonation of explosive under compression loading generates shock and gas energy to extend cracks and cause displacement of fragmented material. Shock energy crushes the material surrounding the explosive loaded zone and gas energy with some delay interval follows just after the shock front to extend cracks beyond the crushed zone for fragmentation and displacement of blasted material. For same explosive parameters, fragmentation and throw varies with site parameters *viz.,* geology and blast design and no single phenomena can universally explain the process of fragmentation. Beyond the plastic and crack zone *i.e.,* in seismic zone, undesired energy is transmitted to cause annoyance to local inhabitants. Accidents due to flyrock, either serious or fatal, are at present averted by implementing suitable arresting devices and proper blast patterns. The unavoidable and unacceptable consequences of blasting *viz.,* ground vibration and noise/air overpressure, have alerted excavation engineers and are presently of great concern for safe blasting operation. Colonization of residential dwellings and multi-storied complexes surrounding the excavation influenced zone enforced the excavation engineers to have very cautious blasting/excavation activity and minimum impact on surrounding structures. Various researchers considering human annoying, disturbances of sensitive devices and structural damage have evaluated vibration parameters (displacement, velocity and acceleration) and correlated peak particle velocity (PPV) measured on ground with structural damage (Crandell, 1949; Medearis, 1977; Nichols *et al*., 1971; Raush, 1950; Siskind *et al,* 1980). For smooth blasting activity and safety of structures various countries have stipulated legislation to limit ground vibration. However, recent investigations both in model and field noted some anomalies during measurement of vibration on structures. It was communicated that instead of peak particle velocity, particle velocity of each orthogonal component and the component triggering the structure to vibrate plays an important role in quantifying safety of structure towards vibration. Furthermore, to evaluate safe limit of structural vibration, communication has been made by various authors that to eradicate interface between ground and structure, monitoring of vibration should be made on structures and not on ground. So, with respect to blast geometry implemented at the site, identification of vibration component having maximum magnitude and the component triggering the structure to vibrate is an essential pre-requisite to maintain safety of structures during excavation. The paper considering different blast designs with 110 mm drill diameter attempted to evaluate vibration magnitude for each orthogonal component and the component triggering the sensor to vibrate at various distances of concern. The paper lastly emphasized that vibration being reflection of blast design implemented, should be properly analyzed for safety of structure prior to its application, especially where structures are in close proximity to the blasting site.

II. BLAST INDUCED GROUND VIBRATION

Blast induced disturbances vary with nature of transmitting medium, characteristics of explosive, blast geometry, borehole pressure, firing pattern and socio-economic condition of the area. According to law of conservation of energy, energy cannot be created nor destroyed, but, can be transformed from one form to other. Similarly, blast-induced ground vibration being a form of energy generated on detonation of chemical energy stored within explosive, the nuisance caused cannot be completely eliminated but can be minimized by application of suitable blast design. The type of propagating wave, body or surface wave will depend upon the type of breakage and distance of measurement from vibrating source. The P- and S-waves, called body waves, travel through the transmitting medium and at free surface between ground and air, the body waves generate a number of surface waves and are characterized by their motion *viz.,* R-, Q- and C-waves *etc.,*. The Rayleigh or R-wave is most commonly observed surface wave carrying the major part of surface ground energy to cause damage to surrounding structures. The other forms of blast wave *viz.,* love or Q-wave and coupled or C-waves are also generated on detonation of explosive within blastholes. Love or Q-waves are characterized by transverse oscillation of particles in the horizontal plane with no vertical displacement and the coupled or C-waves are known by elliptical and inclined particle motion in both vertical and horizontal directions. Characteristics of structural vibration within seismic influence zone will depend upon particle velocity of vibration component triggering the structure to vibrate, dimensional features of structure with respect to direction of propagating vibration wave and the nature of joints between walls and floors of structure. Complaints emanating from blasting are mainly due to annoyance, fear of damage and psycho-physiological perception rather than numerical values of ground vibration. To control damage and protect structures from deleterious effect of ground vibrations, legislation has been stipulated to limit vibration magnitude measured near the foundation of any structure (Figure 1). In recent years, unconventional control strategies *viz.,* neural networks (NN), fuzzy logic, and genetic algorism (GA), etc. are also being used to predict and control ground vibration.

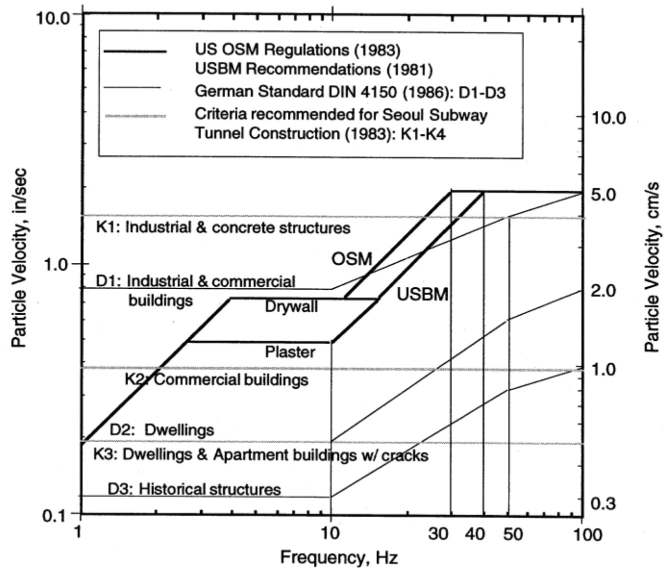

Fig. 1 Vibration standard for various types of structures

III. BREAKAGE MECHANISM

Energy utilized for vibration of ground is about 3-12% of the energy generated in the form of heat of explosion, which counts to 60-70% of energy transmitted to rock (Pastika *et al*, 1995; Scott *et al*, 1993; Spathis, 1999; Sanchidrian *et al*, 2007). It has also been reported that, depending upon blast geometry and explosive characteristics, approximately 2-8% of energy transmitted to rock is utilized in fragmentation of rock mass. Detonation of cylindrical explosive within blasthole provides peak compressive strain on borehole wall and is wasted in pulverizing annular section immediately around the borehole. Beyond the crushed zone, symmetrical propagating tangential tensile wave produces radial cracks and the cracks extend till the stress magnitude exceeds the strength of rock or prematurely arrested by pre-existing cracks within in-situ rock mass. Propagation of cracks depends upon tangential pressure induced by shock wave; reflection of shock wave from free face; wedging action at the crack tip due to high temperature and gas pressure entering narrow radial crack. The explosion gases then stream into the developed cracks for wedging and its extension up to the free face(s). Detachment of rock from its in-situ condition and release of gaseous energy on decaying of strain energy results into release-of-load results into fragmentation. Shear failure also occurs when relative movement of adjacent sections of rock along blast-induced cracks and/or fissures is observed. On completion of extension of radial cracks, the wedge-shaped elements of burden rock suffers bending, and fracturing by flexural rupture in planes normal to the blasthole axis to cause fragmentation. Breakage by in-flight collisions also takes place for certain blast geometries and/or initiation sequences. The above phenomena for breakage of rock mass and its displacement takes place when the implemented blast geometry is optimum with respect to explosive loaded within blasthole and depth of blastholes. But, when burden is about half the depth of blasthole, the phenomena of rock breakage take the principle of crater blasting *i.e.,* breakage of rockmass in the form of inverted vertical cone with vertex at bottom of hole by releasing the gaseous energy through the least resistance path. Detonation of explosive in such conditions releases its gaseous energy mainly by opening of joint planes through the weakest available path *viz.,* the front and top free surfaces. These blasts results into heaving action of blasted fragments with minimum horizontal displacement. However, magnitude of crack density and displacement of blasted material depends upon depth of burial and quantum of explosive loaded per hole.

IV. ROCK BREAKAGE AND VIBRATION MAGNITUDES

Conservation of energy states that detonation of chemical energy transmits unavoidable forms of energies to the surroundings causing nuisance and uncomfortable environment for the people inhabiting within the seismic influence zone. The characteristics and duration of transmitted reaction force depend upon blast geometry, total charge per round, maximum charge per delay and initiation pattern implemented in that round. Utilization of transmitted energy during its path of transmission results into depletion of transmitted energy and reduction in frequency and magnitudes of vibration and acceleration with an increase in distance of measurement (Mandal et al, 2008). The low frequency vibration at longer distances of measurements increases duration of vibration due to low particle velocity resulting into transmission of energy to structure for longer time duration. For normal blast with optimum blast geometry principally known breakage mechanism is observed. Vertical or transverse component triggers the sensor when vibration is monitored at closer distances and longitudinal component triggers the sensor when placed at longer distances, indicating characteristics of wave transmission *viz.,* body and surface waves, at closer and longer distances respectively (Table 1). The difference in triggering component with variation in distance for any sensor will depend upon velocity of transmitted wave within medium, depth of blasthole and explosive loaded within blastholes. However, for typical blast geometry *i.e.,* excessive burden for a given depth of blastholes or in fractured or highly jointed strata, typical breakage mechanism is observed *i.e.,* fragmentation takes place by cratering effect. In such cases, detonation of explosive leads to expansion of borehole and release of gaseous energy by opening of existing cracks during release of pressurized gaseous energy. This results into minimum displacement and heaving of blasted muck. Explosive loaded within blasthole being insufficient to extend cracks towards front burden, gaseous energy trapped within blastholes during its escape through the stemming column opens the joints to cause fragmentation. Depending upon quantum of explosive loaded per hole, heaving and throw of blasted fragments may be observed. High borehole pressure developed due to longer duration of trapped gaseous energy within blastholes high velocity of blast waves may be observed to result into vertical or transverse component triggering the sensor to monitor for even longer distances of measurement (Table 2).

TABLE 1 DETAILS OF BLAST GEOMETRY FOR THE SITES

Site Name	Hole diameter (mm)	Hole Depth (m)	Burden x Spacing (m x m)	Charge per hole (kg)	Total Charge (kg)	Distance of vibration measurement (m)	No. of Data
Site A	110	3	2 x 2.5	2.78	5.56 – 102.86	45 – 130	16
Site B	110	2.0-3.0	(2.4-3) x (2.4-4)	4.4 – 4.83	162 – 464	40 – 166	16
		3.1-5.0	4.0 x 5.0	19 – 25	305 – 1080	52 – 230	24
		5.1-8.0	4.0 x 6.0	28 – 51	250 – 591	52 – 175	34
Site C	110	9.0-9.5	3.5 x 4.0	51 – 77.5	601.5 – 2228.3	65 – 370	61
Site D	110	3.0-4.0	2.0 x 2.5	8.34 – 11.12	75 - 4875	120 - 265	34

TABLE 2 PERCENTAGE OF TRIGGERING AND MAXIMUM COMPONENT MAGNITUDE AT THE SITES

Site Name	Hole Depth (m)	% age of Occurrence					
		Triggering Component			Component Having Maximum Magnitude		
		Transverse	Vertical	Longitudinal	Transverse	Vertical	Longitudinal
Site A	3.0	5.56	33.33	61.11	5.26	47.37	47.37
Site B	2.0 – 3.0	43.75	43.75	12.50	31.25	62.50	6.25
	3.1 – 5.0	4.17	79.17	16.67	16.67	54.17	29.16
	5.1 – 8.0	3.03	81.82	15.15	20.59	41.18	38.23
Site C	9.0 – 9.5	6.35	88.89	4.76	24.59	40.98	34.43
Site D	3.0 – 4.0	20.64	37.93	41.38	37.93	41.38	20.69

V. MATHEMATICAL MODEL

Let vibration generating source be S and monitoring locations be Q and R at horizontal distances L and $L+L_1$ respectively from the vibration generating source. Let the radial distances between points 'S and Q' and 'S and R' be SL and SL_1 respectively (Figure 2). Vibration from source 'S' will travel to sensor location, say R, by two minimum paths *viz.,* along SR or along SQ and QR and the path to trigger the sensor will depend upon velocity of blast wave in transmitting medium and dissipation of energy during its travel. Since, velocity of body wave being higher than surface wave blast waves should reach the sensor 'R' through path SR and trigger the sensor by vertical component of blast wave. But, presence of numerous joint and foliation planes in its path of transmission *i.e.,* along SR, path of transmission will have maximum likelihood of dissipation of energy and delay in reaching the sensor location along the path 'SR' for triggering the sensor to monitor and the sensor may be triggered by the travel path along SQ and QR. So, for same blast it may be observed that irrespective of component magnitude, vertical component may trigger the sensor at location 'Q' and longitudinal component may trigger the sensor to vibrate at longer distances, say 'R'. For same depth of blast hole, an increase in blast geometry *viz.,* burden and spacing, not only increases borehole pressure but also fragments rock by the principle of crater effect. During this process of fragmentation, the radiating seismic energy in perpendicular direction to borehole wall, results into vertical or transverse component of vibration wave to trigger the vibration sensor. The vertical component triggering the sensor for monitoring may be observed when blasting is carried out in close proximity to sensor location or when blasting is carried out at lower benches and monitoring is done on top ground surface. However, presence of interfering medium in path of transmission of blast wave will result into longitudinal component to trigger the sensor to monitor.

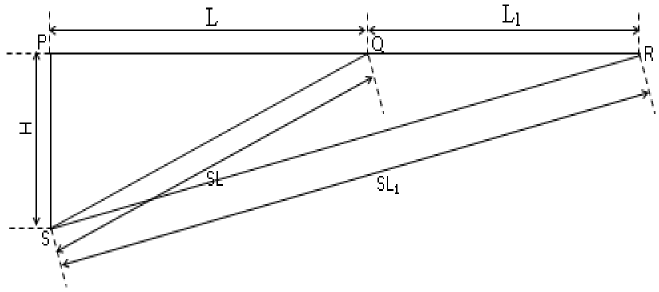

Fig. 2 Straight line schematic diagram showing transmission of blast waves

Mathematically, from Pythagoras Theorem it can be said that

$$SL^2 = H^2 + L^2 .$$

Now differentiating with respect to time (t) we have,

$$\frac{\partial}{\partial t} SL = \frac{\partial}{\partial t} H + \frac{\partial}{\partial t} L .$$

With an increase in L in comparison to H or magnitude of H tending to zero, SL will be almost equal to L. From the above differential equation we therefore find that as H tends to minimum, $\frac{\partial}{\partial t} SL$ tends to $\frac{\partial}{\partial t} L$ and vertical component will trigger the sensor to vibrate. But, presence of bedded structure and attenuation of body wave along SR, wave may travel faster along the path SQ and QR to reach sensor to trigger for monitoring and longitudinal component will trigger the sensor to vibrate. But, with principle of crater method of blasting, borehole pressure being very high, $\frac{\partial}{\partial t} SL$ will be more and vertical or transverse component will trigger the sensor to vibrate even for longer distances of measurement. Similar thing may also occur when H is very high in comparison to L *i.e.,* blasting is carried out at greater depth in comparison to horizontal distance from blasting source.

VI. STRUCTURAL RESPONSE TO GROUND VIBRATION

Blasting activities around civil constructions have potential to cause annoyance or disturbance to humans and if sufficient precautionary measures are not adopted, minor or major damages may also occur in structures. Impact of repeated blasting might also result into damage to structures when magnitude of regular blast-induced vibration exceeds the limit stipulated by the provincial guidelines (Stagg, et al, 1984; Siskind et al, 1980). Environmental changes also result into structural damage. Comparative analyses of strain produced due to blasting (dynamic) and environmental changes (static) communicates that the latter have higher impact than that caused by blasting (Dowding, 1985). Blast loads typically produce strain rate in the range between 10^2 and 10^4 s^{-1}; much lower than dynamic failure loading strain for brick and mortar constructed structures which is approximately 4 times for compression and 6 times for tension (Grote et al, 2001).

The existing damage criteria of various countries are based on correlation of damage in structures with the intensity of ground vibrations (Crandell, 1949; Medearis, 1977; Siskind et al., 1980; Dowding, 1996; Duvall and Fogelson, 1962; Wiss, 1968; and Nichols et al., 1971). Considering frequency of vibration, limits of vibration magnitude has been stipulated for various types of structures. For low-rise structures, soil-structure interaction and amplification of vibration due to resonance are indirectly taken into consideration. The structural parts *viz.,* floors, internal walls, sensitive devices within the structure excited due to ground motion, structural dimension and the type of fixing of such parts to structure are of importance and should be considered to limit vibration magnitude. So, assessment of vibration induced damage should be made on the basis of measurement on structure and not on ground. Longitudinal wave triggering wall of any structure to vibrate acts as moment and amplifies amplitude of oscillation and vibration magnitude with an increase in height of measurement (Mandal et al, 2005 a,b). The bending will be maximum till the application of load and thereafter, the structure will bend along the slope of deflection at the point of application of pressure/stress. Conversely, vertical component triggering the structure to vibrate acts as body wave and is transmitted through the wall of the structure to cause attenuation in vibration magnitude with an increase in height of measurement on structure (Mandal, 2010). Difference in magnitude of vibration and amplitude of oscillation at different floors or walls will result into differential movement of structural frames vis-à-vis development of bending stress on walls to induce cracks/damage of wall plasters. Vibration of any structure triggered by longitudinal or transverse/vertical component will cause damage to structure, but the characteristics and extent of damage will depend upon distance between two consecutive floors, wall thickness, distance between walls present in-line with wave component and height of each structure. Furthermore, considering the seismic impact by orthogonal components of ground vibration on walls or floors for same dimension of a structure, it can be understood that difference in magnitude of amplitude of oscillation at different floors and walls vis-à-vis magnitude of strain developed due to longitudinal component will be much higher than that caused by vertical or transverse components of ground vibration. From Equation (1) it is well understood that difference in magnitude of moment of inertia, I, will result into different magnitude of bending stress on the structure (Figure 3). Moment of inertia for three-dimensional body with respect to any axis is obtained by adding its moment of inertia with respect to parallel centroidal axis, the product of the mass of the body and square of the distance between the two axes. The generalized formula for determination of moment of inertia along any axis can be expressed by Equation (2) and at centroid for each axis can be determined from Equation (3), where, W, is the weight of wall and g is acceleration due to gravity.

$$\frac{M}{I} = \frac{f}{y} = \frac{E}{R} \tag{1}$$

Where,

M = bending moment or resistance to bending,

I = moment of inertia,

f = stress intensity,

y = distance from neutral axis,

R = radius of curvature, and

E = Young's modulus.

$$i^2 = \bar{\imath}^2 + d^2 \tag{2}$$

Where,

i = moment of inertia of three-dimensional body about the axis,

$\bar{\imath}$ = moment of inertia of two-dimensional body about that axis, and

d = distance of centroid along that axis.

$$I_x = \frac{W}{g}\frac{H^2 + B^2}{12};\ I_y = \frac{W}{g}\frac{L^2 + B^2}{12};\ I_z = \frac{W}{g}\frac{H^2 + L^2}{12} \tag{3}$$

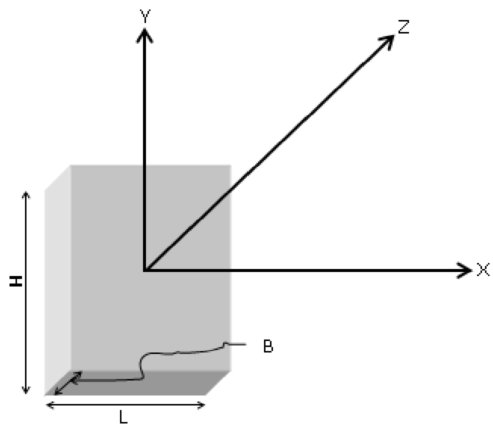

Fig. 3 Dimension of walls along the three co-ordinate axes

Considering magnitudes of moment of inertia along each axis, it is well understood that structure will succumb to maximum damage when wave component strikes in the direction perpendicular to XY plane. Similarly, vibration along vertical or transverse component has to be of much higher magnitude for same magnitudes of deflection in a structure in the directions perpendicular to ZX plane or YZ plane to cause damage to structure.

VII. CONCLUSION

Mechanism of rock breakage is principally followed when magnitude of burden is compatible to drill hole diameter and depth of blast holes. The reaction force for such conditions transmits vertical component of blast wave to have the highest magnitude and triggers the sensor to monitor at closer distances of monitoring. However, at far off distances longitudinal component may have highest magnitude and trigger the sensor to monitor. But, when magnitude of burden is high in comparison to drill hole diameter and depth of blastholes, rock breaks principally by crater mechanism. Compaction of gaseous energy within borehole for longer time duration results into high borehole pressure and release of gaseous energy through top surface. This principle of rock breakage results into vertical component to have highest magnitude and triggers the sensor to monitor even for longer distances of measurement. Considering safety of structure with respect to blast-induced ground vibration, highest magnitude of moment of inertia will be along vertical direction. So, comparatively high magnitude of vertical component will result into less magnitude of bending stress and structures will sustain more stress and succumb to less damage.

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