S. K. MANDAL
M. M. SINGH
and
S. DASGUPTA

Theoretical evaluation of energy from blast-induced vibration waves measured on ground and structure

Legislation of limiting blast-induced vibration level measured near foundation of structure have imposed difficulty in quarrying operation. Confrontation towards excavation work rises to its peak when drilling and blasting activity is carried out in close proximity to structures. Considering the sustaining capacity of structures towards high magnitude blast-induced ground vibration, the paper analyzes characteristics and quantum of energy transmitted to structure at the place of measurement. Theoretical model developed to evaluate wave characteristics and quantum of energy contained in blast wave signatures has been used for analysis. Comparative analysis of wave characteristics and quantum of energy transmitted at different distances/heights of concern is detailed in the paper. The paper firstly makes a comparative analysis of characteristics and energy contained in peak magnitude and wave signatures measured on ground at different distances of measurement and thereafter, compares wave signatures monitored near foundation of structure and first floor of a two storied structure, located within 50 m from blasting site.

Introduction

Drilling and blasting, utilizing only 20-30% energy of heat of explosion, is said to be the most compatible and economical method of excavation. Out of the total utilized energy, percentage of energy wasted in causing environmental discomforts is about 9% as seismic energy in confined blasting condition and varies between 1 and 3% for normal blasting conditions (Sanchidrian et al, 2007). Increased globalization and modernization of excavation sector and its execution in close proximity to structures have raised environmental awareness amongst local people. Vibration being one of the accepted measurable parameter to assess discomfort in respect of damage to structures, legislative bodies of various countries, has enforced limits of vibration magnitude measured near the foundation of the structure. Reportable damage to structures located at far off distances without causing damage to structures at closer distances signifies that magnitude of vibration cannot be the single parameter to assess damage to structures. Present researchers communicate that since soil-structure interaction, depth and width of structure foundation, thickness of wall and dimension of structure with respect to source of vibration influences structural response to blasting, proper analyses of waves should be carried out prior to limitation of vibration magnitude. Researchers also believe that for proper evaluation of blast-induced impact on structures and minimize the error due to soil-structure interaction, vibration should be measured on the receivers end i.e., on structures and not on ground near the foundation of structure. The error associated with densification and liquefaction of soil is also minimized by taking measurements on structure.

Blast-induced stress-strain analysis for different types of structures has been carried out to evaluate the characteristics of strain developed on structures. However, it could not gain its popularity because fixing of gauges is cumbersome and costly, requires high expertise for installation and cannot be used for regular measurement and analyses. Vibration sensors, on the other hand, being easy for installation has gained its popularity for assessment of structural damage. Various authors have also significantly correlated damage of structure with blast-induced ground vibration. Wave signature being the resultant impact of energy transmitted at the place of measurement, characteristics of wave form and thereafter, the energy transmitted should be evaluated from wave signatures to limit safe vibration level. The paper firstly analyzes characteristics of wave form and energy contained in wave signatures for the measurements made on ground at different places of concern. The paper, thereafter, puts forward comparative analyses of blast wave characteristics and energy contained between the measurements made on ground near foundation of structure and at first floor of a two-storied office building located well within 50 m from the blasting site.

Masonry structure

Masonry structure, comprising regular shaped high strength units (bricks) bounded with binding material (mortar) between them are non-elastic, non-homogeneous and anisotropic in nature and behaves typically under load. They are highly

Messrs. S. K. Mandal and M. M. Singh, Scientists, Central Institute of Mining & Fuel Research, Dhanbad and S. Dasgupta, Director Technical, Higher Education, Government of West Bengal, India

resistive to compressive force, but, are very weak in tension. However, in-elastically behaviour even for small distortion is observed under lateral load (McNary and Abrams, 1985; Atkinson and Noland, 1983; Drysdale et al, 1994; Hemant et al, 2007; Doebling et al, 1996). Tensile failure strength of masonry structure depends upon bond strength (mortar strength) between two units, coefficient of friction between mortar and brick and uni-axial compressive strength in both perpendicular and parallel direction to bed joints. Lateral strength of masonry structure 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; Drysdale et al 1994). For non-load bearing walls, flexural strength of masonry is limited by its tensile strength (BIA Technical Reports, 8 & 15; ASTM C 270-02; Wood, S. L., 1995; Wrights, B. T. et al, 1993; Davidsavor et al, 2003). Masonry structure, in comparison to plain cement concrete (PCC) and reinforced cement concrete (RCC) structures, behave indifferently. PCC structures having high compressive strength indicate brittle failure and fails easily with initiation of crack (Paulay, et al, 1992). RCC structure depending upon diameter, quality and density of reinforced material have more flexural strength to sustain deflection vis-à-vis bending stress (Priestley, et al, 2000; Ombers et al, 2000; Aiello and Ombers, 2000).

Literature survey

Deterioration in structure may be either due to environmental or excavation induced forces. Comparative analysis of regular inspections made prior to start of blasting activity, measurement of vibration during blasting and inspection of structures after blasting can identify the cause of deterioration in structures. For proper analyses of structural damage, comparative analysis should start much before start of excavation work and should continue till the end of excavation work. Environmental forces like precipitation, daily and seasonal changes in temperature, change in material properties of building under the influence of moisture and drying, wind speed and direction, soil condition and soil behaviour under structural loading and human activities result into deterioration of structural strength. Excavation induced damage can be identified by visual inspection or experimental tests viz., acoustic or ultrasonic method, magnetic field method, radiography, eddy-current method and thermal field method to quantify magnitude of damage (Chang, 2003; Doherty, 1987; Worden, 2004). Blast-induced vibration measurement or visual inspection only alert the probable presence of damage and do not provide accurate information about the extent of damage. Experimental tests, on the other hand, details extent of damage to the highest level of accuracy, but, are difficult for regular measurement in actual field. Increased excavation activity in close proximity to dwellings have ushered awareness amongst local people regarding deterioration in structural strength and investigation into limiting blast-induced vibration for safety of structures. To reduce blast-induced impact on structures vibration magnitude measured near foundation of structure was specified and the controlling parameters viz., blast design and charge parameters were worked accordingly.To analyze blast-induced impact on structures, Svinkin et al, 2000, a,b, communicated that background vibration status is important and impulse response function prediction (IRFP) method should be implemented for better analyses of structural response to blasting. For safety of structures various researchers have investigated to correlate vibration parameters (displacement, velocity, acceleration and frequency) with observed human annoyance, disturbance of sensitive devices and damage to structures (Crandell, 1949; Medearis, 1977; Sisking et al, 1980; Dowding, 1985). Presently, peak particle velocity (PPV), having better correlation with structural damage, has been widely accepted for legislating safe vibration levels for safety of structures (Duvall and Fogelson, 1962; Wiss, 1968; Nicholas et al, 1971; DIN 4150; Siskind et al, 1980; British Standard BS7385 and USBM's (OSM's) criteria Oriard, 1999, 2002; DGMS Standard, 1997). Present researchers, however, communicate that structural response to external force in terms of quantum of energy transmitted to structure is important and should be evaluated to ascertain safety of structures (Langan, 1980; Siskind et al, 1980; Dowding, 1981; Lagan, 1980; Dowding and Siebert, 2000; Qian, S. and Wang, W., 2002; Zhang et al 2002; Wu et al, 2005; Sun, 2003; Doebling, 1996). Davidsavor et al, 2003 reported that peak particle velocity ranging between 112 and 217 mm/s with an average of 170 mm/s did not cause damage to structures. Similarly, Bay, 2003 commented that the proposition of Chae, 1978, (12.7 mm/s), as safe level of vibration for structures should be the limit for historical buildings and the structures having such safe limit are not suitable for residential purpose. Siskind (2000) using the criteria of OSM and other regulatory bodies have stipulated distance-dependent set of PPV criteria and communicated that the limits specified in DIN4150 are not damage-based, but, are set to minimize perceptions and complains. Magnitude of induced strain in structural components due to differential displacement of floors causes cosmetic cracks or massive failure of structures (Aimone-Martin et al, 2005; Mandal et al, 2005). Structural motion in perpendicular direction to plane of wall (hade joint) and global shear strain causes damage to structure. Investigation by Dowding, 1985 communicated failure strain for gypsum core drywall between 300 and 500 micro-strains and that for bricks between 700 and 1000 micro-strains. Similarly, Kaushik et al, 2007 communicated that for modulus of elasticity between 500 and 7500 MPa, the failure strain varied between 0.0057 and 0.0072 when load varied between 16.1 and 28.9 MPa. Damage analysis due to subsidence states that plaster cracks take place when change in length of structure is less than 30 mm (Price and Freitas, 2008). However, post-tensioning of brick and mortar structure enhances compressive strength of structure and reduces the probability of opening and/or early cracking of joints at early stage (Ganz, 1990). For high frequency blast-induced ground motion, structures do not respond primarily at the global nodes and stability and integrity of RC frames are enhanced with masonry in-fill wall (Ma et al, 2003). For underground blasting and surface measurement, surface reflection of blast waves greatly influence the properties of stress wave on rock surface and on structures (Wu et al, 2005). Numerical analysis of three dimensional damage model indicates that damage of structure to ground vibration is governed by force-stress rather than the commonly adopted in earthquake engineering. Masonry structure is more susceptible to damage than RC frames filled with masonry wall. Out-of-plane damage to structure is more than in-plane damage (Wu et al, 2005; Hao et al, 2002; Mandal et al, 2005), this is because moment of inertia increases with an increase in depth of structure along the line of force. Bending stress being inversely proportional to moment of inertia, magnitude of bending moment/stress decreases when the external force (vibration) is in line with wall of structure and increases when force direction is out-of-plane i.e., perpendicular to the wall structure.

Variation in blast-induced loading rate on structure is mainly due to explosive detonated in same and different delays of a blasting round. Magnitude of strain for any cycle is insignificant if stress applied in the preceding cycle is more and therefore, analyses of loading rate under the influence of blast-induced ground vibration is important to assess damage to structure (Price and Knill, 1966; Birkimer, 1971; Wu and Gao, 1987; Seto et al, 1996). Particle oscillation being the resultant energy generated on detonation of explosive, the paper analyzes characteristics of blast waves and quantum of energy transmitted at the place of measurement. The paper firstly analyses along the distance of measurement on ground and thereafter on different floors of the structure located within 50 m from blasting site. Advanced module software for seismograph has been used for analyses of wave signature recorded at different distances of concern (on ground) and on structure.

Energy model

Blast-induced ground vibration is the reaction force generated on detonation of explosive. The measured magnitude at any distance varies with quality of interference between quantities of explosive energy liberated/generated in different delays of a blasting round and time lapsed between detonation of explosive, fragmentation of rock mass and venting of gas energy. Wave characteristics and magnitude of vibration monitored categorically varies with blast geometry, initiation pattern and quantum of energy dissipated through transmitting medium. Piezoelectric sensors of vibration monitoring instruments when excited above the pre-ascertained threshold value by any external force (blast-induced ground vibration), the instrument starts acquiring data at every infinitesimal time interval (say 0.001 seconds). The acquired data when reproduced provides a graphical plot of wave signature. The schematic diagram of peak magnitude of blast wave and wave signature is shown in Figs.1 and 2 respectively. Advanced module software available for each make/type of seismograph helps to extract the digital magnitude of vibration for each infinitesimal time interval. Wave signatures recorded by any seismograph shows magnitude of vibration (mm/s or in/s) along Y-axis and time in second(s) along X-axis. Since, wave signature monitored by instrument is the result of external force, the characteristic of energy gained by sensor at its location can be evaluated by analyzing the wave signatures. Vibration measured on structure being the resultant of soil-structure interaction and explosive detonated in same and different delays, quantum of energy transmitted to structure can be determined by analyzing the wave signatures measured on structures. Response of structure depends upon strength properties and dimensional features of structure with respect to source of vibration.

Wave length and frequency of vibrating medium being inversely proportional; damaging magnitude for structures due to blast-induced vibration can be properly estimated by knowing the wave length and velocity of peak wave. Since, sensor placed on structure directly measures structural response with respect to external force, monitoring of blast-induced vibration frequency is not essential and can be indirectly evaluated by knowing the sonic velocity of transmitting medium and wave length of forced vibration.

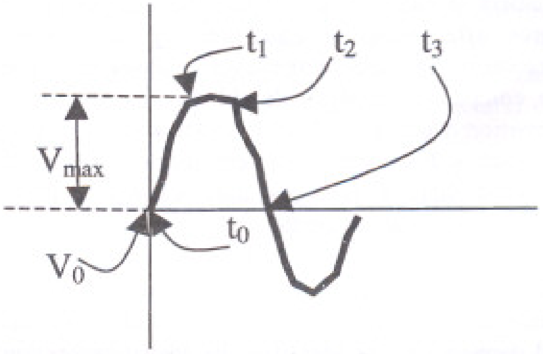

Fig.1 Schematic diagram of peak for a wave signature

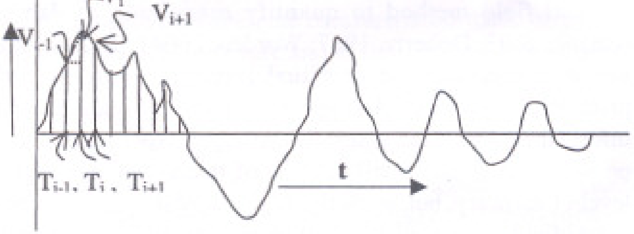

Fig.2 Schematic diagram of waveform for analysis of transmitted energy

Structures when succumbed to resonance i.e., forced vibration frequency matching with natural frequency of structure, vibration monitored on structure will reflect its characteristics i.e., high amplitude vibration or high magnitude of structural oscillation. The characteristics of vibration and energy contained will be comparatively very high when structure frequency is in resonance with forced vibration. However, by placing sensor on ground near foundation of structure, frequency of forced vibration can be monitored. Blast-induced impact on structure also depends upon duration of forced vibration. Magnitude of wave signature (along Y-axis) for any time instant indicates the amplitude at that time instant. Amplitude develops stress on structure and the stress magnitude increases with an increase in amplitude. Any structure is succumbed to maximum stress when same amplitude of vibration is sustained for some time duration. When same amplitude of vibration is sustained for some time duration, the stress developed on structure is high and the quantum of energy transmitted during that time zone is termed as "peak hold energy". Magnitude of stress also varies with loading rate and frequency being inversely proportional to wave length, determination of wave length from wave signature identifies the characteristics of loading rate. Magnitude of acceleration and deceleration of peak magnitude indicates the influencing characteristics of wave(s) transmitted by detonation of explosive in earlier delays of blasting round i.e., constructive or destructive cooperation of charges. High magnitude of acceleration and deceleration indicates high loading rate and high frequency vibration and is acceptable for structures to sustain the impact. On contrary, low frequency blast waves having high energy are not safe for structures and might damage structures even at low vibration magnitude. Since, peak magnitude of wave signature possesses maximum energy, the characteristics of wave viz., wave length, amplitude and acceleration and deceleration can be evaluated from wave signatures, equations 1-4. Magnitude of force generated on detonation of explosive at any time instant can be determined with the help of equation 5. Here, assuming 'm' as mass of sensor under vibration, in grams, and acceleration as 'a' in mm/s^2, the product of both will determine the magnitude of force, F_i, where, $F_i = ma10^{-6}$ N. Multi-channel seismograph with sensors located at vulnerable locations can easily help to evaluate blast-induced stress at various locations on structure. Plot of force diagram and its computer simulation will enable to plot differential forces acting on structure during blasting and knowing the strength properties of structure, the safety of structure can be easily ascertain.

Amplitude of vibration and duration of peak-hold develops stress on structure. Bed joints of masonry structures being the weakest for structural stability, magnitude of stress developed along bed joints during structural oscillation is important. For any time instant, t_i, amplitude is the magnitude of 'Y' component at that location. Similarly, relative displacement is the change in amplitude with respect to time during the vibratory motion of the structure. Magnitude of relative displacement defines the strain/stress rate on the structure during blast-induced vibration transmitted to the structure. Magnitude of maximum and relative displacement during structural vibration can be determined with the help of equations 6 and 7 respectively. Knowing magnitude of amplitude, dynamic stress developed on the structure can be evaluated with the help of equation 8. If amplitude of vibration is sustained for some time duration, i.e., peak magnitude is sustained for some time, the energy transmitted to structure due to bending increases and the structure becomes more prone to damage. Magnitude of maximum peak hold energy and cumulative peak hold energy signifies characteristics of stress developed on structure. Wave signatures monitored for some time duration having several peaks of different magnitudes may sustain for some time duration. Summation of energy content for all such peaks for the total duration of measurement is called cumulative peak hold energy. Cumulative peak hold energy and cumulative energy are the summation of all the peak energies sustained for some time duration and the area between the wave signature and time axis for the time span recorded by the seismograph respectively. Magnitude of peak hold energy (PH_i) and cumulative energy (CPH_i) can be evaluated from wave signatures with the help of equations 9 and 10 respectively. Considering mass of sensor under vibration as 'm' in grams, magnitude of energy or work done by external force can be expressed in 10^{-6} J. When total transmitted energy exceeds the strength that can be sustained by structure, structure is succumbed to damage i.e., plaster cracks or complete failure. For any wave signature, peak of different magnitudes sustaining for some time duration is generally observed to be more for larger diameter blastholes ($\geq$150 mm). Number of such peaks and its duration increases with an increase in blasthole diameter and blast geometry.

Difference in amplitude of oscillation of opposite walls causing differential loading and stress on structure can be evaluated by placing geo-sensors and on opposite walls at different locations of structure. Sensors placed at convenient locations of multi-storied structure helps to know the nodal displacement of each floor and wall and evaluate the characteristics of bending/deflection and stress developed on structure. Longitudinal component of vibration acting parallel to bed joints causes wall deflection and damage to structure. Multi-point monitoring along width and height of structure with respect to longitudinal component of external excitation force, can generate composite bending moment diagram for better understanding of structural behaviour and computer simulation. Knowing strength properties of structure and composite bending moment diagram for each wall, maximum load transmitted to structure can be determined and thereby safety of structure to blast-induced vibration can be estimated. External force transmitted to structure also develops strain and the structure gains some strain energy during forced vibration. Magnitude of strain and strain-induced energy can be determined with the help of equations 11 and 12 respectively.

$$\text{Wavelength} = 2c(T_3 - T_0) \quad \ldots \quad (1)$$

$$\text{Duration of peak} = (T_2 - T_1) \quad \ldots \quad (2)$$

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

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

$$Force = m_i a = m_i \frac{V_i - V_{(i-1)}}{T_i - T_{(i-1)}} \quad \ldots \quad (5)$$

$$\text{Relative displacement (amplitude)} (A_1)$$

$$= V_{inst(i)} - V_{inst(i-1)} \quad \ldots \quad (6)$$

$$\text{Maximum displacement or amplitude} (t_1)$$

$$= V_{inst(i)} \quad \ldots \quad (7)$$

$$\frac{M}{I} = \frac{f}{y} = \frac{E}{R} \quad \ldots \quad (8)$$

$$\text{Peak energy} = V_{phi}\left(t_{(i+1)} - t_i\right) \quad \ldots \quad (9)$$

$$\text{Workdone}$$

$$= m_i \sum_{i=2}^{i=n-1} \left[\left(V_{inst(i)} + V_{inst(i-1)}\right) \times \left(T_i - T_{(i-1)}\right)\right] \div 2 \quad \ldots \quad (10)$$

$$\text{Strain} = \left(V_{inst(i)} - V_{(i-1)}\right) \div V_{inst(i-1)} \quad \ldots \quad (11)$$

$$Strain\ energy = \left[0.5\left(V_{inst(i)} - V_{(i-1)}\right)\left(T_{inst(i)} - T_{(i)}\right)\right]$$

$$\div \left[V_{i-1}\left(T_{inst(i)} - T_{(i-1)}\right)\right] \quad \ldots \quad (12)$$

where,

c = Sonic velocity of transmitting medium
E = Young's modulus,
I = Moment of inertia,
M = bending moment or moment of resistance
y = distance from neutral axis
R = radius of curvature
F = stress intensity

Wave analysis

Piezoelectric sensors on application of external force record fluctuation in voltage. With the help of in-built converter/ software, voltage fluctuation is converted into particle velocity as output of instrument for record and analyses. For each orthogonal components viz., longitudinal, vertical and transverse, instruments detail maximum particle velocity, triggering time and computes maximum acceleration and displacement. The graphical plot recorded by seismographs being the resultant impact of blast geometry, quantum of explosive detonated in same and different delays of a blasting round and properties of transmitting medium, evaluation of wave signature represents quantum of energy transmitted to the sensor at the place of measurement. The paper, firstly, analyses wave characteristics and quantum of energy transmitted to ground for various distances of concern. The paper, thereafter, analyzes vibration measured on ground and roof of first storey for two storied structure. The instruments used for vibration measurement were of Instantel make, Canada.

For 160 mm drill diameter, 7.5 m hole depth and 3.0 m burden and 3.5 m spacing, vibration was monitored at different distances. The blast details, along with recorded vibration magnitude, triggering time, frequency and computed values of acceleration and displacement determined by the instrument for three orthogonal directions is detailed in Table 1. Component wise analysis of data reveals that for most of the blasts instrument was triggered by longitudinal component. Maximum magnitude of acceleration and displacement, as computed by the instrument, were for longitudinal and vertical components respectively. Triggering by longitudinal component (surface wave) possibly indicates destructive interference of body waves during its transmission within the medium. Similarly, maximum displacement for vertical component signifies the characteristics of strata movement on detonation of explosive. Instead of front movement of burden for breakage of rock mass surrounding the blast hole i.e., perpendicular to hole axis breakage of rock mass was observed by vertical movement i.e., vertical movement of rock strata/parallel to hole axis. This was possibly because of high burden magnitude in comparison to depth of blasthole i.e., high stiffness ratio and hard strata resulted into maximum displacement along vertical component. Wave characteristics and energy contained for the blast event having maximum magnitude of vibration i.e., fourth blast, was analyzed. Peak magnitude of each component was also analyzed to evaluate its characteristics and energy contained at different distances of measurement. Comparative analyses of magnitudes of acceleration, deceleration, peak-hold energy and wave length for peak magnitude of each component are detailed in Table 2 and Fig.3. For transverse component, sensor located at 110 m distance, recorded two peaks of same magnitude at two different time zones. For the first peak, magnitude of acceleration and deceleration being the highest peak-hold energy was less. For second peak, having less magnitude of acceleration and deceleration, peak sustained for some time duration i.e., peak hold energy was higher than first peak, indicating higher magnitude of strain and quantum of energy than the first. Comparative analysis with distance of measurement reveals that magnitude of strain and energy transmitted increases with decrease in the magnitudes of acceleration and deceleration.

Table 1: Particle velocity characteristics with distance of measurement

	Charge per hole/ maximum charge per delay (kg)	Total charge/ no of hole (kg)	Distance (m)	Peak particle velocity (mm/s)	Particle velocity characteristics					
					Particle direction	Particle velocity (mm/s)	Frequency (Hz)	Triggering time (sec.)	Peak acceleration (mm/s)	Peak displacement (mm)
1	37.5/75	450/12	150	3.03	Trans	2.29	18	0.118	0.0398	0.0183
					Vert	2.29	8	0.161	0.0265	0.0975
					Long	1.65	23	0.084	0.0398	0.0164
			185	2.59	Trans	1.33	8	0.163	0.0199	0.0233
					Vert	1.33	8	0.091	0.0133	0.0202
					Long	2.54	11	0.190	0.0199	0.0364
			240	1.43	Trans	0.635	8	0.202	0.00829	0.0122
					Vert	0.746	10	0.271	0.0116	0.0131
					Long	1.37	9	0.184	0.0133	0.0208
			270	0.810	Trans	0.635	9	0.197	0.00663	0.0104
					Vert	0.635	9	0.074	0.0133	0.0113
					Long	0.699	11	0.239	0.00663	0.00887
2	37.5/75	750/20	140	2.88	Trans	1.78	20	0.232	0.0265	0.0241
					Vert	2.03	10	0.278	0.0398	0.0936
					Long	1.90	27	0.196	0.0398	0.0188
			170	2.64	Trans	1.40	16	0.191	0.0199	0.0169
					Vert	2.35	10	0.179	0.0265	0.0367
					Long	2.16	15	0.296	0.0265	0.0281
			225	1.30	Trans	1.11	11	0.44	0.0116	0.0151
					Vert	1.21	11	0.313	0.00994	0.0167
					Long	0.937	17	0.208	0.0116	0.0126
			260	1.17	Trans	0.635	12	0.348	0.0133	0.00803
					Vert	1.02	10	0.319	0.0133	0.0176
					Long	0.635	20	0.132	0.0133	0.00784
3	37.5/75	900/24	120	3.06	Trans	2.29	37	0.223	0.0597	0.0173
					Vert	2.1	24	0.154	0.0464	0.0131
					Long	2.6	47	0.072	0.0795	0.0135
			150	2.61	Trans	1.78	18	0.23	0.0265	0.0165
					Vert	2.29	13	0.149	0.0398	0.0931
					Long	1.90	19	0.179	0.0265	0.0141
			250	1.21	Trans	0.937	11	0.203	0.0116	0.0122
					Vert	0.540	6	0.253	0.00994	0.0126
					Long	0.857	7	0.335	0.00829	0.0142
			280	0.857	Trans	0.508	18	0.039	0.0133	0.0054
					Vert	0.699	12	0.012	0.00663	0.0093
					Long	0.508	12	0.317	0.00663	0.00586
4	37.5/ 112.5	925/25	110	5.2 MMP	Trans	3.68	43	0.034	0.0795	0.0238
					Vert	3.81	13	0.122	0.0795	0.0401
					Long	4.06	28	0.07	0.0795	0.0226
			160	3.79 MMB	Trans	3.56	27	0.132	0.0729	0.0212
					Vert	1.59	39	0.146	0.0464	0.02
					Long	2.16	11	0.142	0.0398	0.0216
			200	3.02 B	Trans	2.27	8	0.35	0.0149	0.0426
					Vert	2.05	9	0.4	0.0182	0.0364
					Long	2.29	9	0.428	0.0199	0.0371
			225	1.89 MM	Trans	1.46	13	0.186	0.0199	0.0196
					Vert	1.33	11	0.223	0.0265	0.0181
					Long	1.52	9	0.113	0.0199	0.0213

TABLE 2: DIFFERENT CHARACTERISTICS COMPUTED FROM OF PEAK MAGNITUDE FOR EACH COMPONENT

Instrument distance (m)	Direction	Acceleration (mm/s^2)	Deceleration (mm/s^2)	Peak energy (x10-1 erg)	Wave length × C mm
110	Transverse	666.1017	612.069	0	0.0234
	Transverse1	314.5299	645.7627	0.00368	0.0372
	Vertical	314.5299	155.5102	0.003429	0.0742
	Longitudinal	616.1765	431.9588	0.00812	0.037
160	Transverse	362.0253	432.0513	0.003204	0.0332
	Vertical	251.7241	230.4348	0	0.0254
	Longitudinal	184.6154	63.25301	0	0.0898
200	Transverse	85.55133	72.28916	0.00227	0.121
	Vertical	71.73145	76.04563	0.0041	0.1132
	Longitudinal	86.74242	82.05128	0	0.1074
225	Transverse	68.2243	72.15909	0.00292	0.082
	Vertical	64.87805	59.375	0.00133	0.0878
	Longitudinal	2.147803	65.17857	0.00152	1.3686

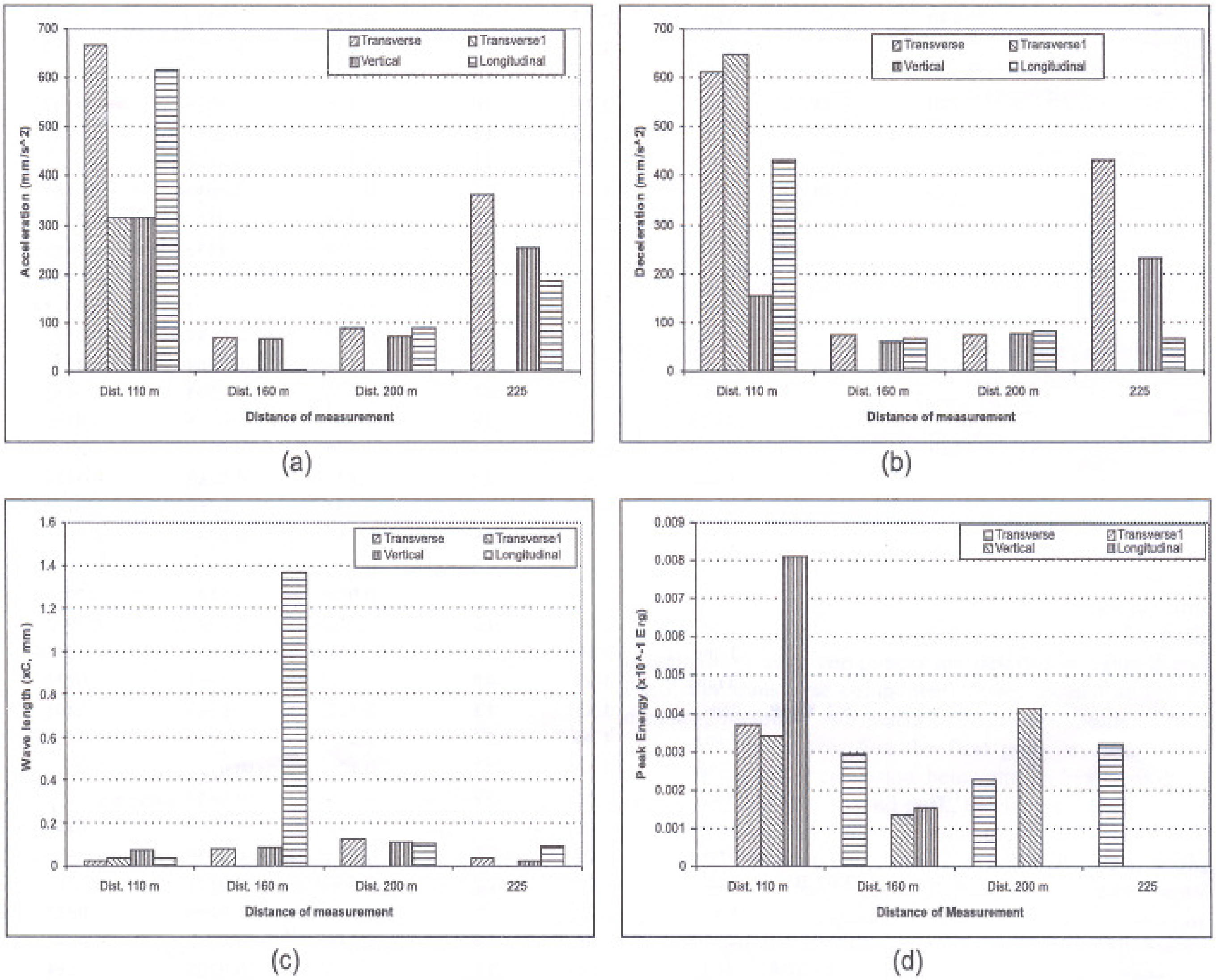

Fig.3 Wave characteristics measured at different distance of measurement

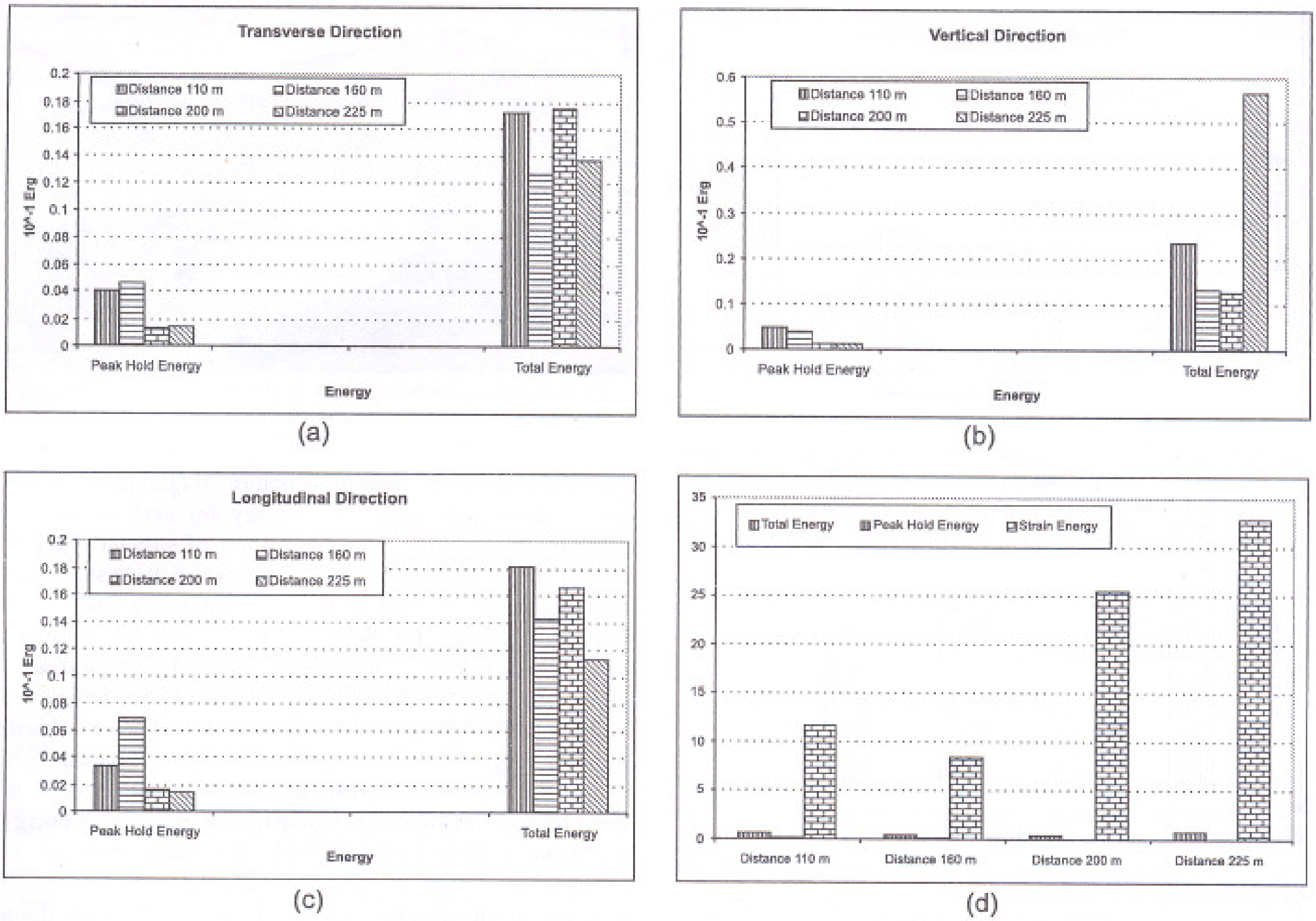

Fig.4: Wave energy of each component for different distances of measurements

Sometimes blast-wave signature comprise number of peaks of different magnitudes. These peaks, depending upon blast geometry and initiation pattern, sustain for some time duration to develop strain on the transmitting medium. The vibrating medium is continuously strained during vibration and therefore, quantum of energy transmitted can be evaluated. Peak hold energy and cumulative energy transmitted at the place of measurement has been evaluated and graphically plotted in Fig.4. The peak hold energy for both longitudinal and transverse component, except at 160 m distance, indicates a moderate decay with an increase in distance of measurement. However, increase in energy content at 160 m distance possibly indicated constructive cooperation of charges/energies. Structures around such locations might be under high stress and might succumb to damage without causing any damage to structures at other distances. The vertical component indicated a steady decrease in peak hold and total energy. At farthest distance of measurement an enhanced magnitude of total energy possibly indicated the influence of total charge. Comparative analysis of energies with distance of measurement is shown in Fig.4(d). Magnitudes of strain and energy content for the three orthogonal components are shown in Fig.5. For both transverse and vertical components a steady increase in strain energy, except for 160 m distance, was observed with an increase in distance of measurement.

Influence on structure for close distance monitoring was also evaluated. Characteristics of wave and energy contained within blast wave were evaluated with an increase in height of measurement on structure. Vibration was measured at ground, near foundation of structure and on roof of first storey of an old office building located well within 50 m from the blasting site. The structure under consideration had maximum dimension along the longitudinal component of blast waves. Fig.6 shows location of structure with respect to the blasting sites. The drill hole diameter and depth of blastholes for these blasts were 160 mm and 7 m respectively. Vibration data and computed magnitudes of acceleration, deceleration, triggering time and frequency of vibration for each component are detailed in Table 3. For both the measurements, reduction in vibration magnitude was observed with an increase in height of measurement. Peak magnitude of each component was analyzed to compare characteristics of blast wave measured on ground and roof of first floor of the structure. Considering wave signature of peak magnitude, characteristics of peak were analyzed and are

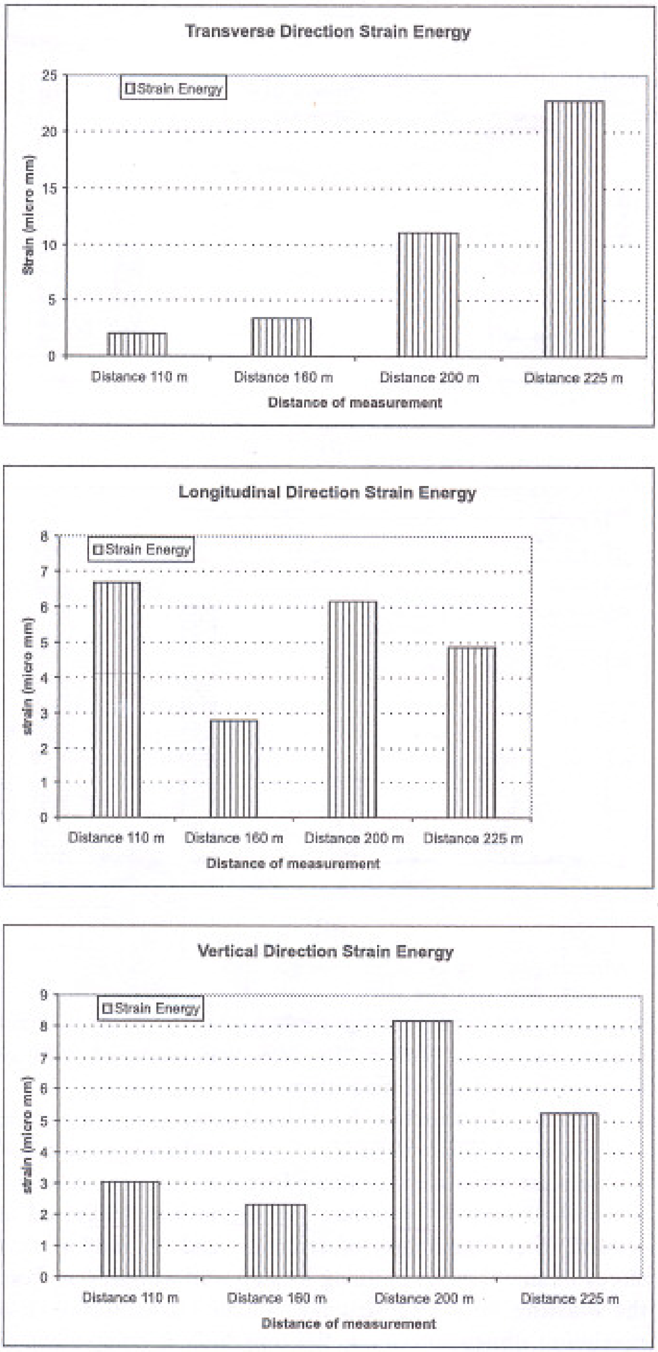

Fig.5: Strain energy for different components at various distances of concern

detailed in Table 4, Fig.7. High magnitude of acceleration and deceleration are less harmful than low magnitudes. Peaks with high magnitude of acceleration and deceleration will not sustain for longer time duration and their peak-hold energies will also be nominal. High stiffness ratio in blast geometry is also reflected by magnitude of peak hold energy for vertical component.

Fig.6 Blasting sites with respect to the structure under vibration measurement

Wave signatures of each component having several peaks of different magnitudes may sustain for some time duration to develop strain on structure. Magnitudes of peak-hold energy and cumulative energy for each orthogonal component measured near foundation of structure and on roof of first floor have been evaluated from wave signatures and graphically plotted in Fig.8. Comparative analyses of peak-hold energy for both the blasts indicate a typical relation. For first blast, an increase in quantum of peak-hold energy is observed with an increase in height of measurement on structure. However, for second blast, located very close to structure, reduction in peak-hold energy is observed with an increase in height of measurement on structure. Comparative analyses of energy for ground floor between both the blasts indicate an increase in energy content with decrease in distance of structure from vibration source. However, for first floor, reduction in energy is observed with decrease in distance of structure from vibration source. Analyses of cumulative energy for both the blasts indicate decrease in cumulative energy content with an increase in height of measurement on structure. However, comparative analyses of cumulative energy between two blasts indicate an increase in energy content with decrease in distance of measurement. Comparison of amplification factor of cumulative energy between ground and first floor for both the blasts reveal that amplification factor for ground floor was higher than that for first floor. Comparative analysis of blast wave energy transmitted to structure reveals that high magnitude of acceleration resulted into absorption of energy during its transmission from ground to first floor. Hence, for close range blasting, ground floor may succumb to damage without imparting any damage to upper floors.

Characteristics of strain developed on structure due to change in amplitude for three orthogonal components and for each floor viz., near foundation of structure and on roof of first floor, are plotted in Fig.9. For both the blasts, graphical plot indicates maximization of strain and its energy content for ground floor i.e., high absorption of energy in ground floor during its transmission to first floor. For first blast, transverse component experiences maximum strain, whereas

TABLE 3: BLAST DETAILS AND MEASURED VIBRATION MAGNITUDE AT GROUND AND 1ST FLOOR OF AN OLD OFFICE BUILDING

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			Roof of 1st Floor			Ground			Roof of 1st Floor		
Horizontal distance (m)	35			35			15			15		
Peak particle velocity (mm/s)	18.4			8.89			71.3			16.1		
	Trans	Vert.	Long	Trans	Vert.	Long	Trans	Vert.	Long	Trans	Vert.	Long
Particle velocity (mm/s)	14.7	7.11	12.2	4.06	6.35	7.87	48.4	59.9	14.7	8.13	14.2	13
Frequency (Hz)	43	73	16	22	11	8	34	32	43	24	32	23
Triggering time (ms)	0.066	0.023	0.068	0.146	0.193	0.26	0.077	0.098	0.066	0.086	0.197	0.089
Peak acceleration 'g'	0.504	0.398	0.292	0.0795	0.119	0.0663	1.38	4.08	0.504	0.119	0.318	0.199
Peak displacement (mm)	0.052	0.05	0.0788	0.0642	0.0673	0.110	0.201	0.274	0.247	0.0495	0.0672	0.0874

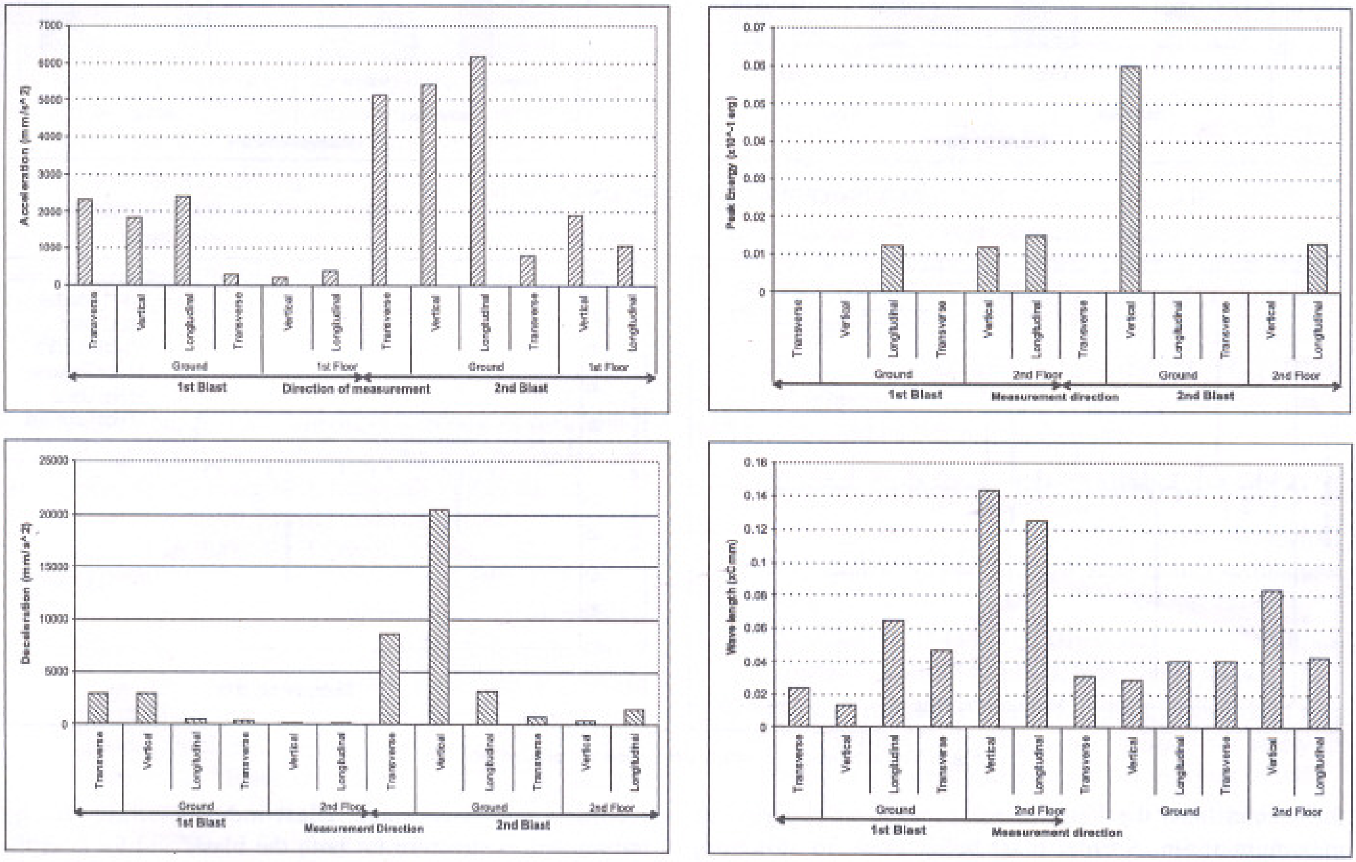

Fig.7 Wave characteristics of peak magnitudes

TABLE 4 : DIFFERENT CHARACTERISTICS COMPUTED FROM OF PEAK MAGNITUDE FOR EACH COMPONENT

Blast No.	Floor No.	Direction	Acceleration (mm/s²)	Deceleration (mm/s²)	Peak energy (x10-1 erg)	Wave length × C mm
1	Ground	Transverse	2316.18	2902.04	0	0.0234
		Vertical	1823.08	2975.86	0	0.0136
		Longitudinal	2383.67	463.5	0.01219	0.0644
	Roof of 1st floor	Transverse	298.55	427.55	0	0.0468
		Vertical	178.36	170.39	0.012065	0.1438
		Longitudinal	371.71	196.26	0.014953	0.125
2	Ground	Transverse	5131.633	8584.48	0	0.0312
		Vertical	5455.56	20493.1	0.05994	0.0294
		Longitudinal	6184.06	3189.05	0	0.0412
	Roof of 1st floor	Transverse	795.92	759.81	0	0.041
		Vertical	1905.13	435.8	0	0.0832
		Longitudinal	1085.47	1557.95	0.01295	0.043

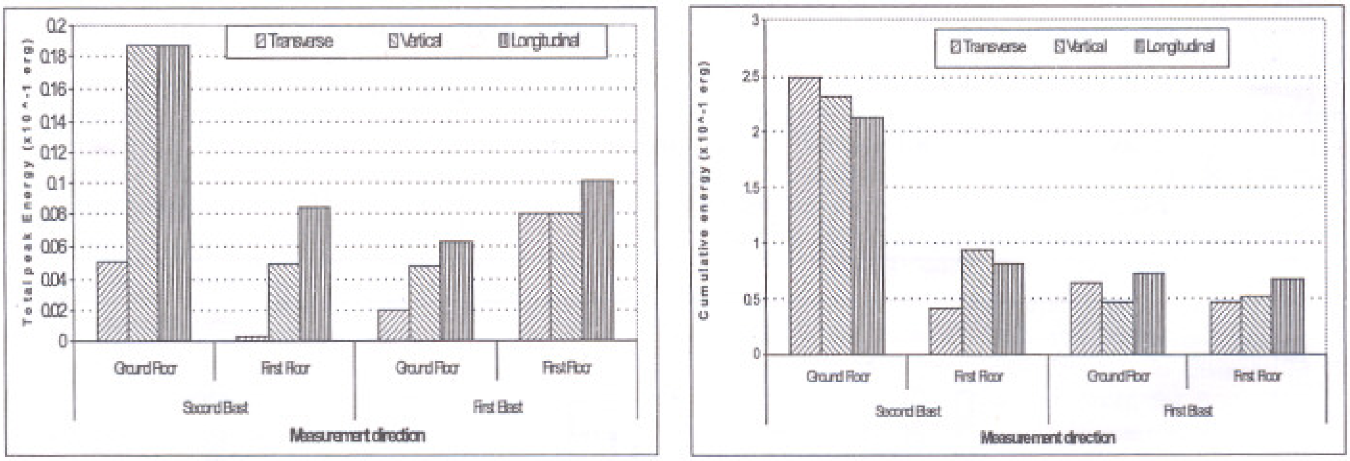

Fig.8 Energy of blast waves for ground and first floor

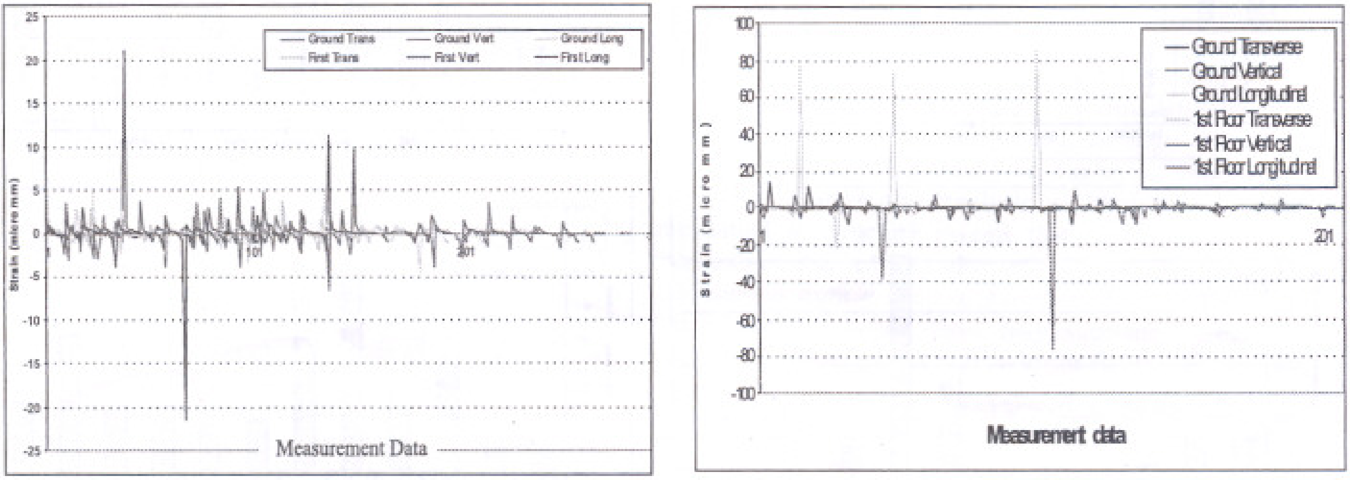

Fig.9 Characteristics of strain developed on ground and first floor

for second blast the longitudinal component experiences maximum strain. Second blast being close to structure, magnitude of strain was comparatively higher than that recorded for first blast. Blast-induced strain energy transmitted to structure for both the blasts and for both the floors is shown in Fig.10.

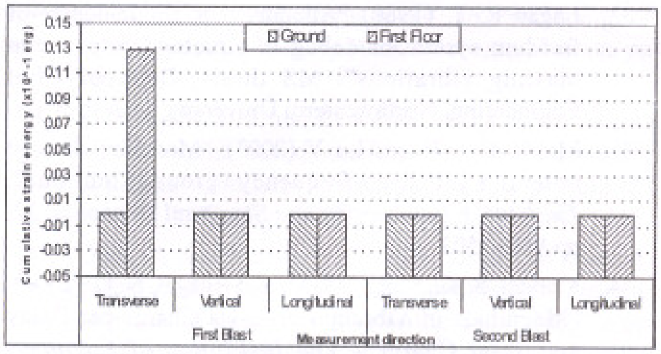

Fig.10 Cumulative strain energy transmitted to structure at different floors

Conclusion

Vibration magnitude measured near foundation of structure does not signify the damaging level of structure. Before construction of any building, pre-blast survey and characteristics of peak magnitude and energy contained in blast signatures should be evaluated for safety of buildings. Wave characteristics and energy contained within blast-wave being the resultant impact of various parameters viz., explosive quantity detonated in same and different delays, blast pattern and properties of transmitting medium, the same should be analyzed to limit vibration magnitude for safety of structure. Characteristics of peak magnitude and energy contained within wave signature should be evaluated before limiting vibration magnitude for safety of structures. Blasting in close proximity to structures with high vibration magnitude may not damage structure if the energies content is less than that can be sustained by the structure. For blasting close to structures, induction of damage to ground floor may occur before causing any damage to upper storeys. Multiple interferences of blast waves detonated in different delays of a blasting round might enhance energy content within blast waves at any particular location and might cause damage to structures without causing damage at close or far off distances.

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