Tunnel-Soil-structure Interaction Subjected to Blast Loads of Varying Intensities

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ABSTRACT: Vibrations induced from blasting are common near mining and construction sites. Buildings which are in close proximity to direct or indirect explosions are highly vulnerable to excitations. The effect of vibrations is more pronounced in the presence of a tunnel. In this study two velocity time histories with different frequencies are applied at the crown of the tunnel. Building storeys are varied as 2, 4 and 8 storeys. Two different combinations of geo-mechanical properties of soil and structure are considered. Three dimensional Distinct Element Code are used for the study. Response velocity, displacement and stress time histories were noted at various target points in the model. Irrespective of the soil type, concentration of velocity in the top floors was more than the bottom floors. Stress concentration at the sides of the tunnel in the presence of building and tunnel are higher than the stress concentration generated only in the presence of a tunnel. Amplification of velocity was observed when the frequency of the input wave was 2Hz.

1 INTRODUCTION

Underground tunnels which are at shallow depths are highly vulnerable to seismic excitations and blast induced vibrations. It was often felt that the extent of vibrations that a surface structure would experience is much more than the vibrations and subsequently the damage an underground structure would experience. A number of case histories have proved otherwise. Although all vibrations may not induce damage to underground structures like tunnels, detailed research carried out by several researchers have indicated that damage may vary from a simple spalling of concrete to the extreme case of collapse of the entire tunnel. A detailed explanation on the causes of tunnel failure, types and the mechanism for finding out strains are described by several researchers [Dowding and Rozen (1987), John and Zahrah (1987), Hashash et al. (2001), Wang et al. (2001)]. Most researchers have concentrated their studies on damage assessment in tunnels subjected to seismic excitations due to earthquake loads. However, a few researchers [Lu et al. (2005), Tian and Li (2008), Liu (2009), Wei et al. (2011)] have carried out detailed numerical investigations of tunnel subjected to blast loads. Their main focus of study was finding out the Peak Particle Velocities (PPVs) at various locations of tunnel, by converting the pressure generated on blasting, to a triangular velocity history (stress wave) on the inner lining of the tunnel

2 OUTLINE OF INVESTIGATIONS

A parametric study was carried out incorporating various input velocity histories and application of velocity history at crown of the model as described below.

2.1 *Details assigned to strata*

Studies were carried out taking a case study of a tunnel in South India. The tunnel crown is at a depth of -8m from the surface. Diameter of the tunnel taken into consideration was 6.1m. Dynamic load was applied to the tunnel without consideration of building load and subsequently, the displacement on applying dynamic loading was noted. Two different soils with varying stiffness were taken into consideration. The properties assigned to the strata are shown in Table 1. S-1 is a C-Ø soil with cohesion 9kPa and angle of internal friction 29˚. S-2 is also a C-Ø soil having a cohesion of 12kPa and angle of internal friction 32˚.

2.2 *Details of the building*

Framed 2, 4 and 8 storey buildings without brick-infill walls were considered for the analysis (Fig. 1). Columns are of size 0.35mx0.45m with an axial stiffness of 128MN. Slab is assigned a thickness of 0.15m. Beams have cross-sectional dimension of 0.3mx0.35m with axial stiffness of 85.8MN and bending stiffness 0.876MN-m^2. The footings were of 2m x 2m dimensions and located at a depth of 1.5m from ground level.

Table 1. Properties Assigned to materials

Type of material	K (kPa)	G (kPa)	γ (kN/m^3)	C (kPa)	μ
S-1	$13.3e^5$	$2.85e^5$	21.0	09	0.40
S-2	$3.30e^6$	$1.10e^6$	22.0	12	0.35
Structure	$1.42e^7$	$1.10e^7$	25.0	-	0.18
Tunnel	$1.30e^7$	$1.05e^7$	24.0	-	0.20

K is the Bulk Modulus
G is the Modulus of rigidity
γ is the unit weight
C is the cohesion
μ is the Poisson's ratio

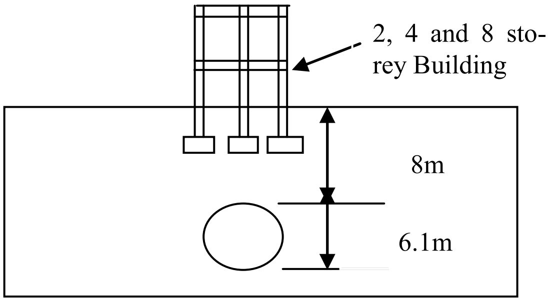

Fig.1 Details about tunnel and building used in model

2.3 Dynamic loading

In three dimensional Distinct Element Code (3DEC), the input wave may be a stress wave/ pressure wave or a velocity wave. However Fan et al (2004) have proved in their research, using discrete element method, that in layered/jointed strata a velocity time input is more effective than a pressure time history as the former type effectively transmits input waves without any reflection back into the media and therefore in the present study a velocity wave was used as an input in the model.

Velocity history was applied at the crown of the tunnel, assuming an in tunnel explosion. Total duration of the blast is 1s and time step used for the analysis was Δt = 0.096ms. Two blast waves of different frequencies were used for the analysis. In the first case a blast wave of PPV 21.5mm/s and frequency of 45 Hz was applied. In the second case a blast wave of PPV 45mm/s and frequency of 2Hz was applied (Fig. 2).

A linear elastic model was assumed for the tunnel liner, building and soil strata.

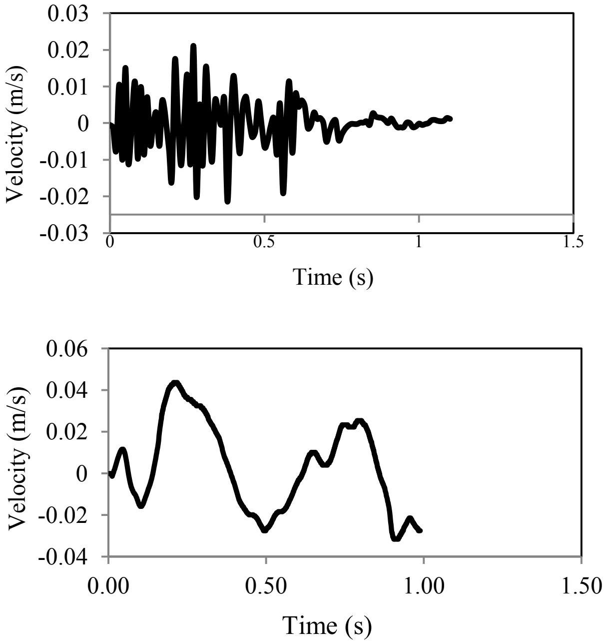

Fig. 2 Velocity time history of 45Hz and 2Hz waves applied to the model

A model showing the discretization with finer mesh refinement for the building is displayed in Fig. 3.

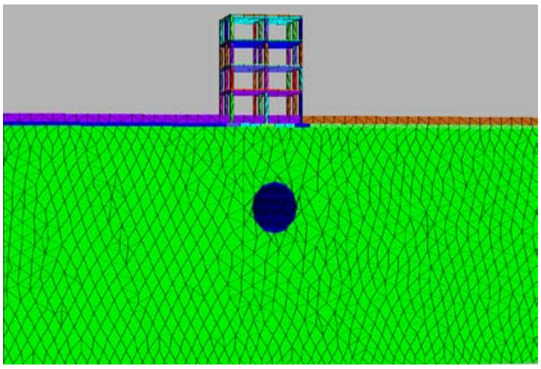

Fig. 3 Meshed model of soil and building

3 ANALYSIS OF RESULTS

Three dimensional dynamic soil structure interaction studies were conducted for the tunnel with varying building storeys. The effect of soil-structure interaction was considered by considering two different soil-structure types represented by S-

1 and S-2 as explained in the preceding sections. Prior to the application of actual dynamic loads the natural frequency of the building with the tunnel embedded at a depth of 8m from the surface was analyzed. The natural frequency in the presence of tunnel for 2 storey building is 1.5Hz and 2.2Hz, 1Hz and 1.3Hz in 4 storey building and 0.4Hz and 0.6Hz for 8 stories, in soil types S-1 and S-2 respectively.

Results of the analysis are presented in two stages

1. Analysis of velocity and displacements
2. Analysis of stresses surrounding tunnels and in building

3.1 Analysis of velocities and displacements in the structure

Displacements and PPV’s in the building prior to application of dynamic load were compared to the ones generated after application of dynamic load. Figs. 4, 5 and 6 indicate soil-tunnel-structure response of the 2, 4 and 8 storey building subjected to velocity wave inputs at the crown of the tunnel.

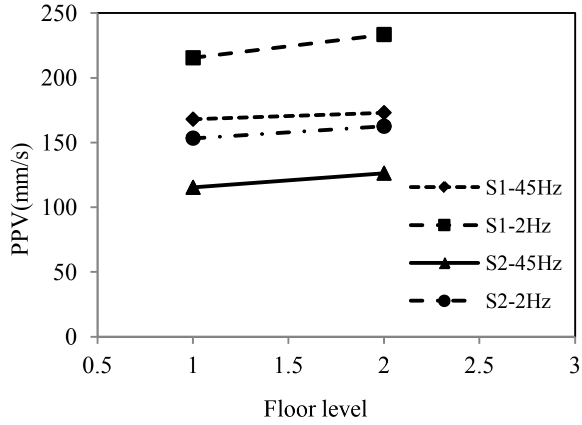

Fig. 4 PPV'S generated at different floor levels of two storied structure

Response of the building to low frequencies was prominent, as the natural frequency of the 2, 4 and 8 storey building considering soil structure interaction was 1.5, 1.0 and 0.4 for S1. This indicates that when the frequencies of input wave motion matched the natural frequencies of the building it led to amplification of vertical velocities.

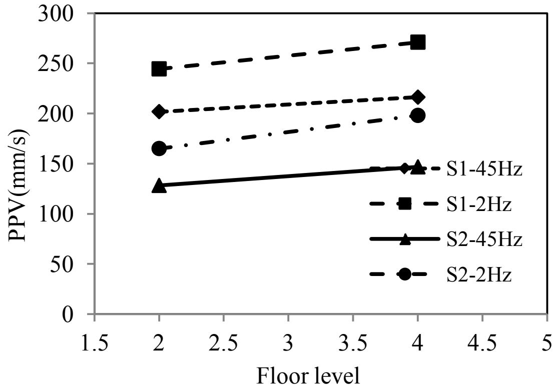

Fig. 5 PPV'S generated at different floor levels of four storied structure

For a given building PPV's at the top of the building was greater than PPV's at the preceding floor. Vertical velocities were higher at the beam of 2nd floor compared to the beam at 1st floor level of a two storey structure. Thus a velocity history at the top of 2, 4 and 8 storey structure was more than the velocity history at bottom floors. This is in conformity with studies carried out by Singh and Roy (2010).

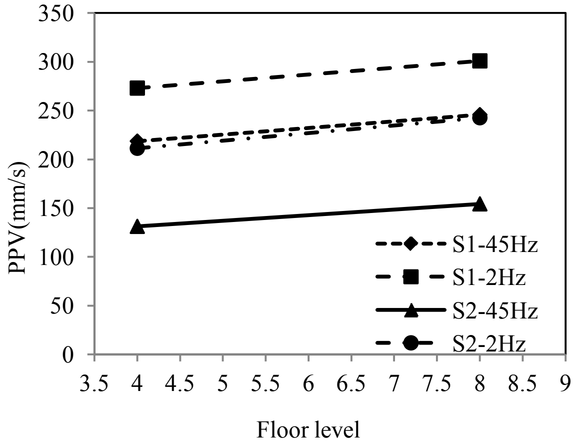

Fig. 6 PPV'S generated at different floor levels of eight storied structure

Higher the storeys, greater is the amplification of vertical velocities. Earthquake motion with peak horizontal velocities, applied to the base of the model indicated maximum horizontal displacement at the top floors than bottom floors indicating that cantilever action is prevalent at the top floors with maximum displacement noted at the top floors. Even in the present case when the model is subjected to vertical time histories, the PPV’s at the building top are more than the preceding floor due to cantilever action. The effect is more pronounced in higher storeys and on softer soils.

Regarding frequencies of the input wave, maximum magnification of velocity amplitudes occurs in structures where in the input wave has a frequency which is equivalent to the natural frequency of the building. The above results are in conformation with results from field investigations conducted by Singh and Roy (2010).

Since blast waves do not produce horizontal drifts compared to vibrations produced by seismic excitations, only vertical displacements at various floors of the building were monitored. Vertical displacements due to application of dynamic input of 45Hz, 2Hz and 85Hz were 1.79mm, 5.95mm, 2.13mm in the 1st floor of two storey structure and 1.82mm, 6.3mm, 2.2mm in the second floor of two storey structures (S-2). This indicates that there is linear relationship in increase in PPV's and increase in displacements. Similar observations were also noticed in 4 and 8 storey building and in varied soil types.

3.2 *Analysis of stress surrounding tunnels and in building*

The concentration of stress at the side of the tunnel, prior to considering building loads, was 1.08MPa, which increased to 1.24MPa, 1.3MPa respectively on considering building loads, and on the application of the 45Hz, 2Hz wave. Peak Stress concentration at the beams of the top floors was more than the concentration of stress at the bottom floors (Table 2).

Table 2. Vertical stress at different locations around the tunnel (S-2)

Observation points in the model	Major Principal Stress (σyy), MPa	
	2Hz	45Hz
Side of tunnel	1.30	1.240
Crown of tunnel	0.58	0.183
1st floor beam	0.28	0.023
2nd floor beam	1.76	0.156

This observation indicates that there is more damage in the top floors and sides of the tunnel at frequencies closer to the natural frequency of the soil-tunnel-structure. Superior material models will definitely capture the failure pattern in different components of structure which is not captured in the current study.

4 CONCLUSIONS

The current study assesses the magnitude of displacements, on subjecting the tunnel to dynamic loads.

1. Results of the analysis indicate that for a given building, maximum peak velocity response occur in the beams of the top floor.

2. With an increase in storey, increase in PPVs were noticed in the top floors indicating greater cantilever action in higher storey structures than short rise structures.

3. Greater displacements generated at the building top resulted in greater concentration of stress in beams of top floors which might eventually lead to greater damage.

4. Maximum concentration of stress occurred at the tunnel sides. Magnitude of stress increased at the tunnel sides on including building loads.

REFERENCES

Dowding, C.H. and Rozen, A.,(1987)., Damage to rock tunnel from earthquake shaking, J. Geotech. Eng. Div., ASCE, 104:175-191.

Fan, S.C., Jiao, Y.Y. and Zhao, J., (2004)., On modelling of incident boundary for wave propagation in jointed rock masses using discrete element method, Computers and Geotechnics, 57-66.

Hashash, Y.A., Hook, J. J., Schmidt, B. and Yao, J.I.C., (2001)., Seismic design and analysis of underground structures, Tunneling and Underground Space Technology, 16: 247-293.

John, St. C.M. and Zahrah, T.F., (1987)., A seismic design of underground structures, Tunneling and Underground Space Technology, 165-197.

Liu, H. (2009)., Dynamic analysis of subway structures under blast loading, Geotechnical and Geological Engineering, 27: 699-711.

Lu, Y., Wang, Z. and Chong, K.,(2005)., A comparative study of buried structure in soil subjected to blast load using 2D and 3D numerical simulations, Soil Dynamics and Earthquake Engineering, 275-288.

Singh, P.K. and Roy, M.P.,(2010)., Damage to surface structures due to blast vibration, International Journal of Rock Mechanics and Mining Sciences, 47, 949-961.

Tian, L. and Li, Z. (2008), Dynamic response analysis of a building structure subjected to ground shock from a tunnel explosion, International Journal of Impact Engineering, 1164-1178.

Wang, W.L., Wang, T.T., Su, J.J., Lin, C.H., Seng, C.R. and Huang, T.H.,(2001)., Assessment of damage in mountain tunnels due to the Taiwan Chi-Chi earthquake , Tunnels and Ug. Sp.Tech., 16, 133-150.

Wei, H., Jian-yun, C. and Jing, G.,(2011)., Dynamic analysis of subway station subjected to internal blast loading, J. Cent. South Univ. Technol, 18:917-924.