16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 4027

Registration Code: S-T1461911897

ELASTO-PLASTIC ANALYSIS OF DELHI METRO UNDERGROUND TUNNELS UNDER SEISMIC CONDITION

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Abstract

Underground Structures are strategic elements in transportation and utility networks, like tunnels in metropolitan cities for mass rapid transit system, water conductor systems, roadway/ railway tunnels in hilly areas, large underground gas and petroleum storages, etc. The importance of these structures makes their vulnerability to earthquakes a very sensitive issue. A large earthquake would not only cause potential loss of human lives but can also damage lot of other infrastructures. This can result in severe economic losses, especially in view of the time required to restore the functionality of the network. Seismic analysis of underground structures involves the interaction with several disciplines including soil, rock and structural dynamics, structural geology, seismo-tectonics and engineering seismology.

Underground structures cannot be treated as completely exempt damage during ground shaking, as demonstrated by 1995 Kobe earthquake, 1999 Chi-Chi (Taiwan) earthquake, and 2004 Niigata earthquake, where several underground structures suffered severe damages. Hence, the associated risk may be quite high. Seismic response of underground structures is basically controlled by the response of the surrounding ground and by the imposed ground deformation and not by the inertial characteristics of the structure itself. For these reasons, it is very important to study how metro tunnels suffer damage during earthquakes so as to protect human life and the service efficiency.

A typical section between Rajiv Square and Patel Square of DMRC (Delhi Metro Rail Corporation) tunnels in Connaught Place, New Delhi, India has been considered for analysis. This section is situated on the Yellow line (line-B6) which was constructed in Phase-1 of the work of DMRC. Finite element analysis of soil-tunnel system has been performed for Uttarkashi 1991 and Chamoli 1999 earthquakes. Elasto-plastic behaviour of soil was simulated using Mohr-Coulomb yield criterion. The response of the system has been obtained in the form of horizontal displacement-time history and induced acceleration-time history. Similarly, maximum forces including axial force, shear force and bending moments induced in RC liners during shaking and also at the end of earthquake have been studied.

Displacements in both soil medium and RC liners of the tunnel were found to increase significantly due to earthquake. Elasto-plastic behaviour of soil-tunnel system was compared with the corresponding elastic response. Nonlinear static analysis of the system has shown that forces in RC liners (axial force, shear force and bending moment) increase due to nonlinearity of the soil mass. Elasto-plastic seismic analysis suggests that – i) non-linearity of soil causes large deformations in soil-tunnel system, and ii) forces in RC liners reduce due to plasticity of soil when dissipation of seismic energy occurs through plastic zone mobilized around the tunnel periphery. If these forces exceed the permissible stresses in liners, the transportation network can suffer damage which can affect the serviceability of such infrastructures.

Keywords: Metro tunnels; Elasto-plastic; seismic response.

1. Introduction

Seismic response of an underground structure is basically controlled by the response of the surrounding ground and by the imposed ground deformation and not by the inertial characteristics of the structure itself, as the response to such an event is substantially dependent on the induced ground deformation. For these reasons, it is very important to study how metro tunnels suffer damage during earthquakes so as to protect human life and the service efficiency. Mohammad et al. (2005) [1] has shown that increasing structural dimensions of lining in static design cannot always be a reliable method against earthquake loading, because this would increase the rigidity of lining and therefore, would increase the effect of earthquake loading. Bilotta et al. (2008) [2] compared the pseudo static analysis with full dynamic analysis using FEM. Modification factors of usual pseudo-static formulae earlier proposed by Wang (1993) were modified, which take into account the kinematic interaction between the tunnel and ground during shaking. Chen et al. (2008) [3] have shown that interaction of shallow tunnel and horizontal interface was severe under dynamic loading, and severe dynamic stress concentration phenomena occur near the tunnel. Amorosi and Boldini (2009) [4] have concluded that seismic event can produce a substantial modification of loads acting in the lining, leading to permanent increments of both hoop force and bending moment. Benguo and Zhiqiang (2011) [5] have inferred on basis of their work that vertical acceleration would lead to great destruction and should be taken into account in the process of seismic assessment of shallow tunnels. Beshrat et al. (2012) [6] have observed an amplification of dynamic stress around tunnel. In weaker soil, the amplification of acceleration was more than in hard soils. Cheng (2012) [7] has demonstrated that damage potential of a tunnel is maximum, when the tunnel lies at a depth that is close to 0.25 times the seismic wavelength, hence shallow tunnels in weak rock and deep tunnels in competent rocks are particularly vulnerable. Closed formed solutions for seismic analysis are also available in literature as given by [8, 9, 10, 11]. In this paper, a typical section of a metro tunnel has been considered for analysis. Finite element analysis of soil-tunnel system has been performed for Uttarkashi 1991 and Chamoli 1999 earthquakes.

2. Outline of problem and numerical modelling

City of Delhi lies in Zone – IV of the earthquake zoning map of India (zone-V being the most critical zone). A typical section of DMRC (Delhi Metro Rail Corporation) tunnels in Connaught Place between Rajiv Square and Patel Square has been considered for analysis. The geometric and other details of the problem are as follows: Diameter of Tunnels is 6.26 m with an overburden depth of 16.87 m. Reinforced Concrete (RC) liners, with a thickness of 0.28 m, have been used as a permanent support system. Elastic modulus of RC liners, E_c is 3.16 x 10^7 kPa and the Poisson's ratio is 0.15. DMRC tunnels have been excavated through the alluvium deposits, generally known as Delhi silt. For the present study, engineering properties of alluvium have been adopted from [12, 13], and the variation of elastic modulus (E) of Delhi Silt with depth has been summarized in Fig.1. The thickness of layers 1, 2, 5 is 10 m each and that for layers 3, 4 is 15 m each. In-situ unit weight, γ_{bulk} and saturated unit weight, γ_{sat} for all layers were found to be 18 kN/m^3 and 20 kN/m^3 respectively. No water table was encountered. Cohesion, c of Delhi silt has been taken as zero (cohesionless silt) and friction angle (φ) and the values of Dilatational angle, ψ were found to be 35° and 5° respectively. Damping in soil and RC liners was treated as 5 % and 2 % respectively.

Problem of Delhi metro underground tunnels has been simulated in PLAXIS 2D and dynamic analysis performed to understand the seismic behavior. 2D plane strain analysis has been carried out with rectangular domain, 140 m x 60 m, using 15-noded triangular elements for the soil mass. Elasto-plastic behaviour of soil domain has been simulated by using Mohr-Coulomb yield criterion. The RC liners were modeled using 32 plate bending elements. No slip condition has been assumed between the tunnel and surrounding soil. For dynamic analysis, viscous absorbent boundary, proposed earlier by Lysmer and Kuhlmeyer (1969) [14], was used to represent the displacement condition along both vertical boundaries.

Earthquake was applied at the base of the model. Newmark's time integration scheme was used in the analysis.

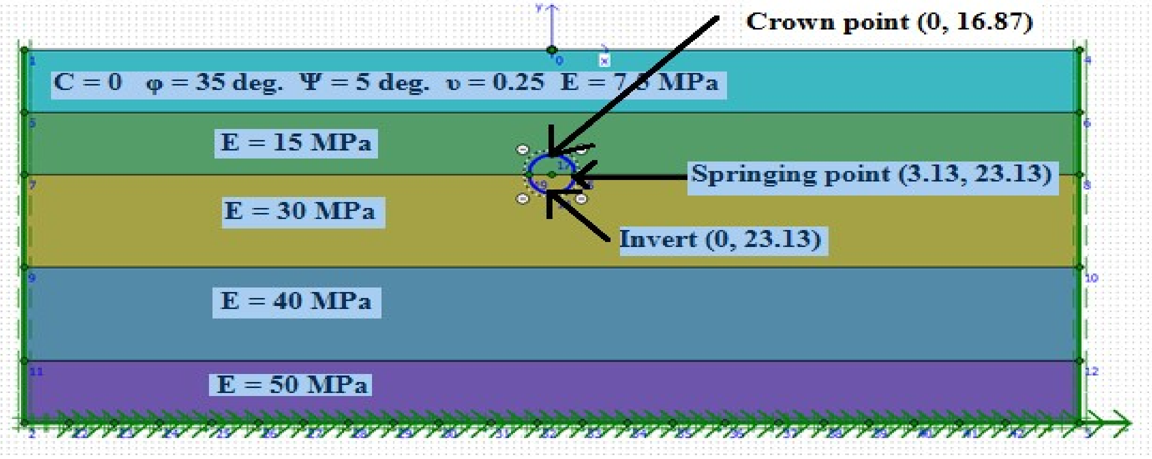

Fig.1 - Geometry of physical model

Attempt has been made in this study to obtain the response of Delhi Metro tunnels to relatively a recent earthquake, namely the 1999 Chamoli earthquake and 1991 Uttarkashi earthquake of the lower Himalaya. Time histories of horizontal and vertical components of Chamoli and Uttarkashi earthquakes (A_x and A_y) are presented in Fig. 2 & 3. Analysis has been carried out for both horizontal and the vertical components of both the earthquakes.

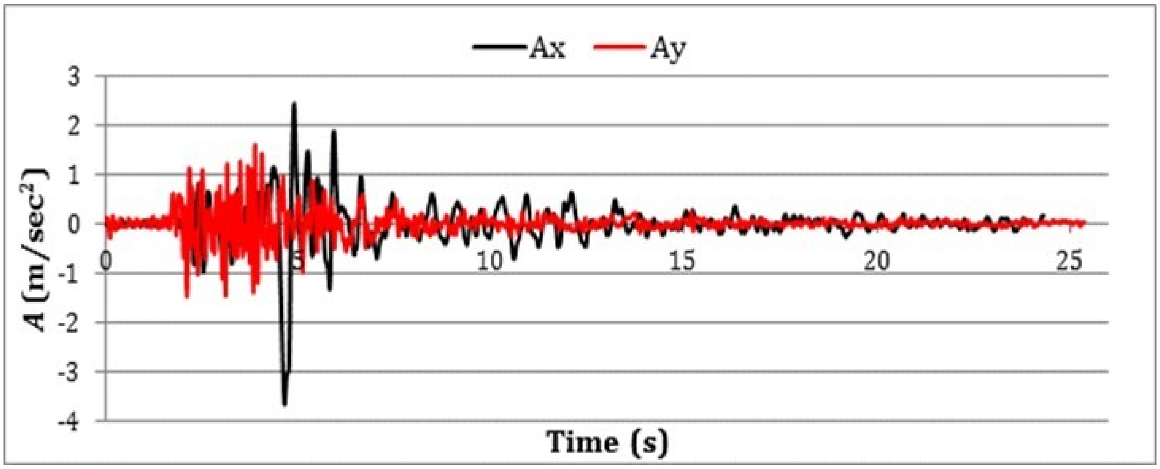

Fig. 2 - Horizontal and vertical acceleration (Ax, Ay) - time history (1999 Chamoli earthquake, India)

3. Stages of analysis

Stage 1: Includes creation of geometry of soil domain and tunnel, and definition of material properties. The tunnel was treated as already excavated. Static boundary conditions are first applied.

Stage 2: Apply static loading which includes in-situ stresses and other loading, if any. Static analysis of the whole system was first carried out and the resulting stresses were stored as initial stresses in the whole system. This defines the state of stress surrounding the tunnel before the occurrence of an earthquake.

Stage 3: For dynamic analysis, the boundaries are treated as viscous absorbent boundaries and corresponding constants involved are defined. Volume contraction was not considered. Apply the time history of earthquake loading along the base of the model and carry out seismic analysis. Results during the earthquake and after the earthquake have been obtained.

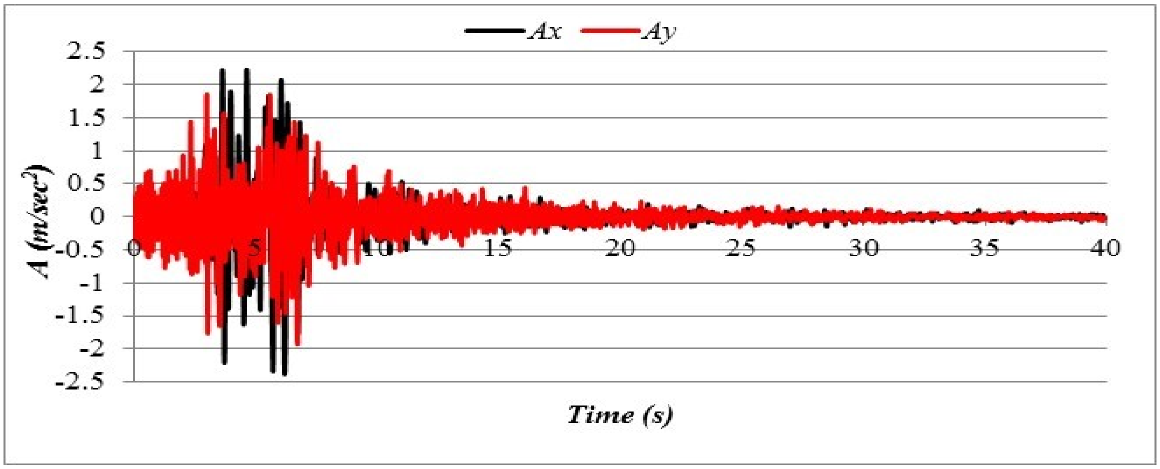

Fig. 3 - Horizontal and vertical acceleration (Ax, Ay) - time history (1991 Uttarkashi earthquake, India)

4. Results and discussion

As stated earlier, a typical section of DMRC (Delhi Metro Rail Corporation) tunnels in Connaught Place between Rajiv Square and Patel Square in New Delhi has been considered for analysis. The seismic analysis has been carried out to obtain the response of tunnels to 1999 Chamoli and 1991 Uttarkashi earthquakes of the lower Himalaya. Entire problem including the loading and the boundary conditions has been defined in Art. 2 above. Figure 1 shows the reference X-Y coordinate system adopted and also the imposition of viscous absorbent boundary along the two vertical sides. Typical monitoring points like crown **(**0, -16.87), invert (0, -23.13) and the springing points (3.13, -20), (-3.13, -20) of the tunnel have been identified in this Fig. 1.

4.1 Response of soil-tunnel system to horizontal component of earthquakes

The analysis of Delhi Metro tunnels has been carried out considering 5% damping for soil mass, and 2% damping for RC liners, for the horizontal component of both earthquakes. Results of elastic-plastic analysis have been obtained using PLAXIS 2D and presented here for discussion.

4.1.1 Horizontal displacement response

Table 1 shows the maximum displacements in soil and RC liners which have occurred during and after application of the earthquakes. It has been found that maximum horizontal displacement at ground surface is of the order of 137.27 mm for Chamoli earthquake and 112.61 mm for Uttarkashi earthquake. In RC liners, the horizontal displacement has been found to be maximum at the springing point; maximum horizontal displacement of the RC liner has been found to be 96.28 mm for Chamoli earthquake and 118.69 mm for Uttarkashi earthquake.

Table 1 - Maximum displacements (U_{max}) in tunnel and soil medium due to horizontal component of earthquake (EQ)

U_{max} (mm)	**Static**		**1999 Chamoli earthquake**				**1991 Uttarkashi earthquake**			
	Soil	**RC liners**	**Soil**		**RC liners**		**Soil**		**RC liners**	
			During EQ	After EQ	During EQ	After EQ	During EQ	After EQ	During EQ	After EQ
U_X	13.74	14.57	137.27	26.63	96.28	20.34	112.61	24.88	118.69	38.88
U_Y	25.60	26.94	3.47	0.49	27.77	27.29	3.41	3.39	26.98	26.92

The time history of horizontal displacement at ground surface (0, 0) and at crown, invert and springing point of the tunnel has been plotted in Figs. 4a, 4b, 4c and 4d. The time history shows difference in response at these locations. During the earthquake, displacement initially shoots up in soil-tunnel system and ends up in to some residual displacement, for both the earthquakes.

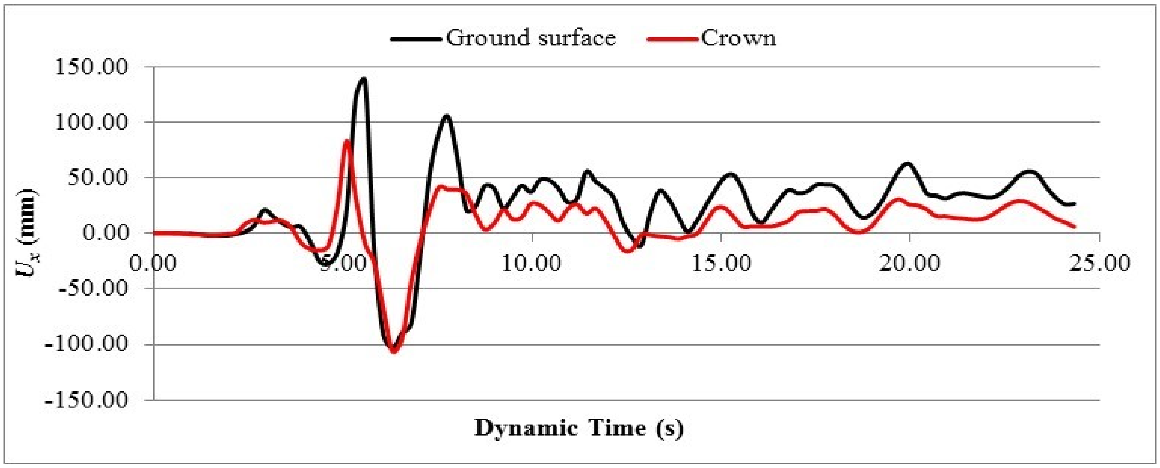

Fig. 4a - Time history of horizontal displacement (U_x) at different locations (1999 Chamoli earthquake, horizontal component)

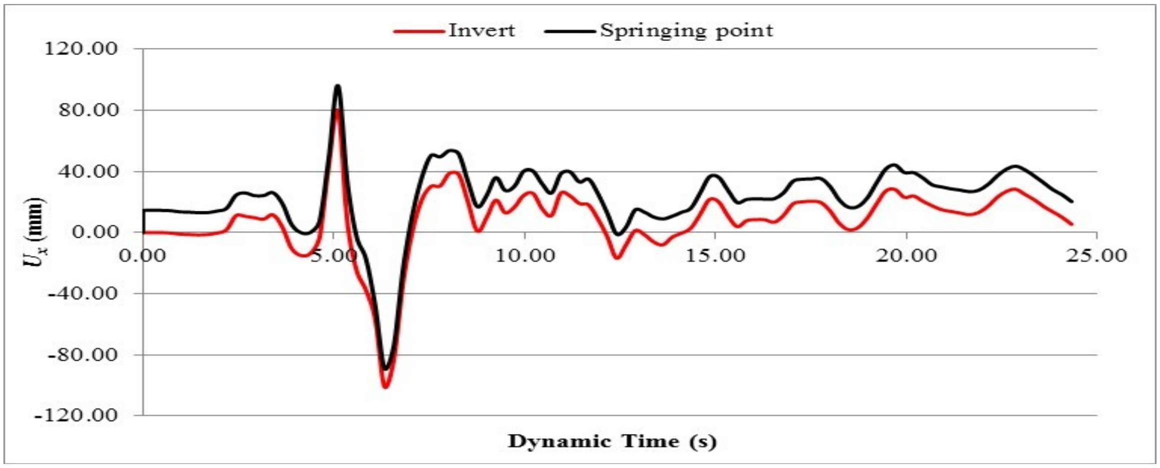

Fig. 4b - Time history of horizontal displacement (U_x) at different locations (1999 Chamoli earthquake, horizontal component)

4.1.2 Vertical displacement response

The time history of vertical displacement at different points, for Chamoli and Uttarkashi earthquakes has been presented in Figs. 5a and 5b respectively. Maxima vertical displacement is observed at the invert of tunnel for both the earthquakes and is of the order of 27.77 mm for Chamoli earthquake and 26.98 mm for Uttarkashi earthquake. The time history shows only marginal variation in the magnitude of vertical displacement with time at these locations.

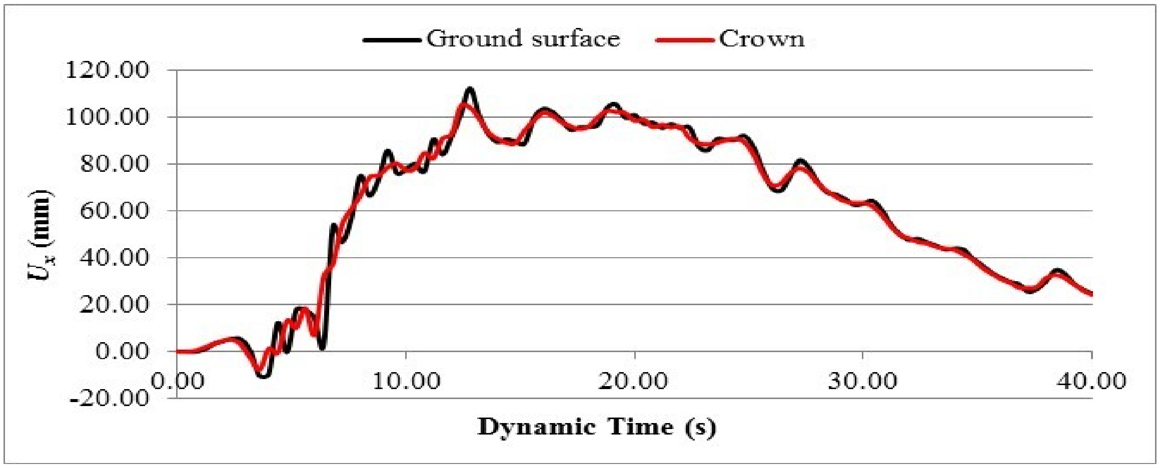

Fig. 4c - Time history of horizontal displacement (U_x) at different locations
(1991 Uttarkashi earthquake, horizontal component)

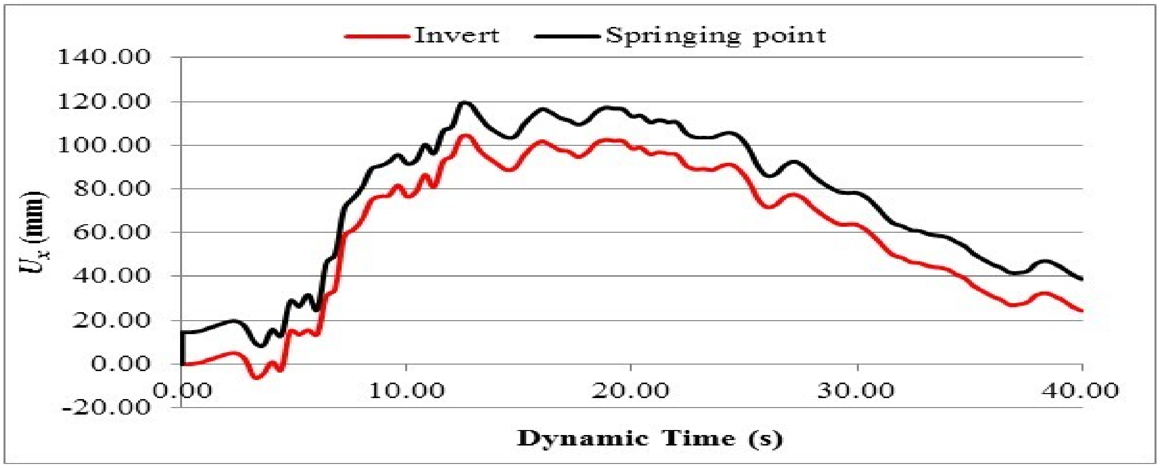

Fig. 4d - Time history of horizontal displacement (U_x) at different locations
(1991 Uttarkashi earthquake, horizontal component)

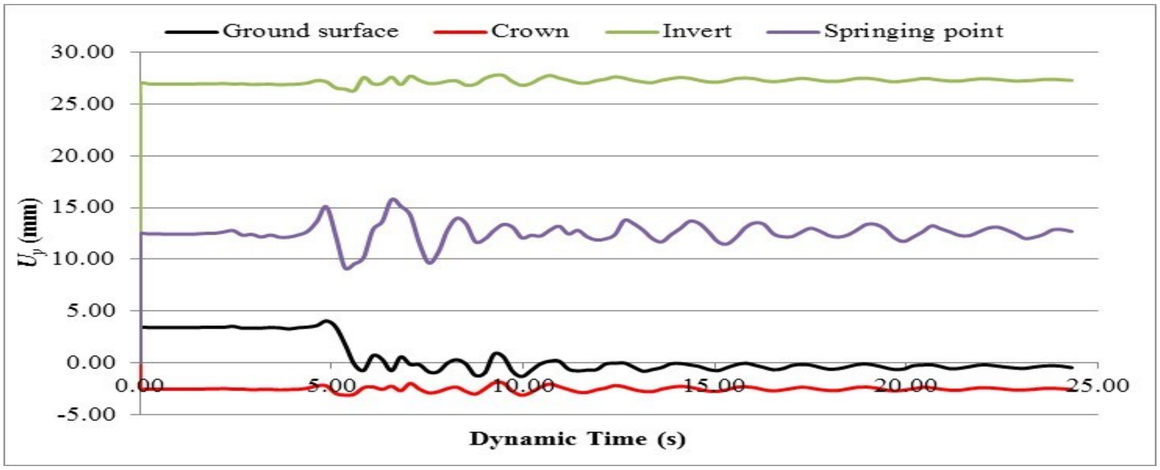

Fig.5a - Time History of Vertical displacement, U_Y (x 10^{-3} m) at different locations of soil-tunnel system due to 1999 Chamoli earthquake (horizontal component)

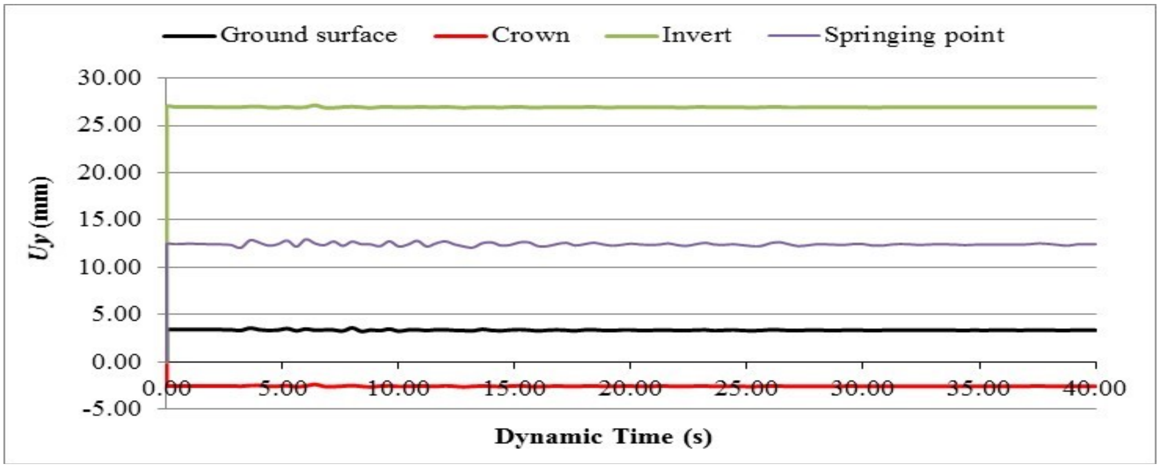

Fig. 5b - Time History of Vertical displacement, U_Y (x 10^{-3} m) at different locations of soil-tunnel system due to 1991 Uttarkashi earthquake (horizontal component)

4.1.3 Forces in RC liners

The maxima values of axial force, shear force and bending moment experienced in the RC liners at any time during the earthquake are tabulated in Table 2 along with the values for the static case. It can be seen that axial force is maximum at springing points during shaking for both the earthquakes with a maxima value of 1.07 x 10^3 kN/m for Chamoli earthquake and 1.04 x 10^3 kN/m for Uttarkashi earthquake, whereas at the end of shaking, the residual value of axial force has been found to be 1.03 x10^3 kN/m for both earthquakes**.** Shear force varies significantly around the periphery of RC liners and the maximum shear force has a value of 229.95 kN/m for Chamoli earthquake and 184.00 kN/m for Uttarkashi earthquake whereas at the end of shaking, the residual value of shear force has been found to be the same as the respective static values. Maximum bending moment around the periphery of the liners during shaking were found to be 344.62 kN-m/m for Chamoli earthquake and 277.56 kN-m/m for Uttarkashi earthquake. At the end of shaking, the residual value of bending moment has been found to be 273.31 kN-m/m for Chamoli earthquake and 269.79 kN-m/m for Uttarkashi earthquake. It can be observed from Table 2 that the forces and the bending moment increase in RC liners quite significantly during the earthquake.

Table 2 - Extreme Forces in RC liner due to horizontal component of earthquake

Maximum forces in RC liner	**Static**	**1999 Chamoli earthquake**		**1991 Uttarkashi earthquake**	
		During shaking	**After shaking**	**During shaking**	**After shaking**
T (kN/m)	1030	1070	1030	1040	1030
V (kN/m)	176	229.95	178.52	184.0	176.10
M (kN-m/m)	269.66	344.62	273.31	277.56	269.79

The combined stress in RC liners due to both axial force and bending moment works out to be 30.20 MPa for Chamoli earthquake and 24.96 MPa for Uttarkashi earthquake which when compared to the permissible stress in M40 concrete is smaller and hence the RC liners are safe.

4.1.4 Induced horizontal acceleration

It is worth knowing the level of acceleration attained at different points in soil-tunnel system at different times during the earthquake shaking and hence the time history of horizontal acceleration has been plotted in Figs. 6a and 6b at tunnel crown and at the ground surface. For Chamoli earthquake, it can be seen that it is the ground surface that experiences maximum horizontal acceleration of 4.16 m/sec^2 equivalent to 0.424g or 1.13 times of the maximum applied horizontal acceleration (3.66726 m/sec^2) whereas acceleration level experienced at the tunnel crown is only 2.82 m/sec^2.

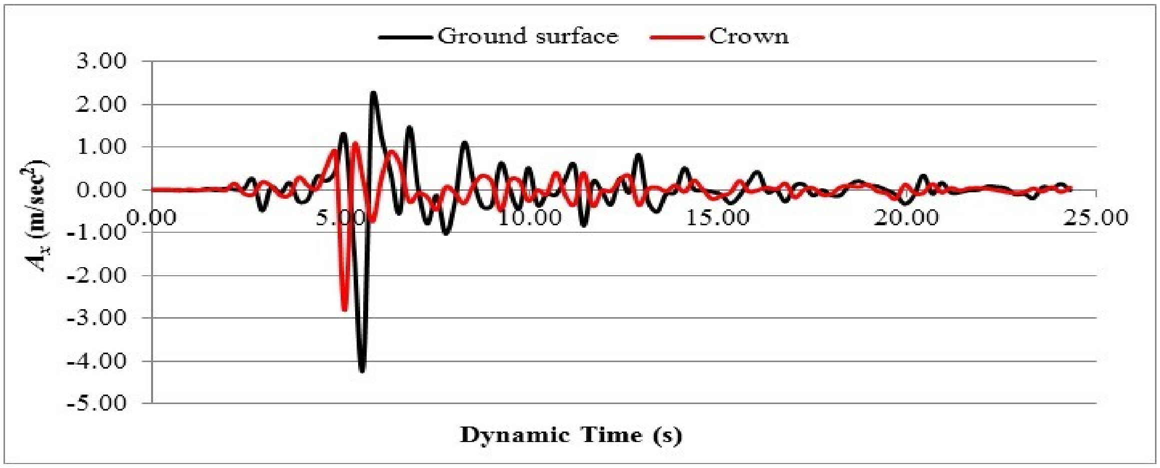

Fig. 6a - Time history of horizontal acceleration at different locations around tunnel Periphery due to 1999 Chamoli earthquake (horizontal component)

For Uttarkashi earthquake, it can be seen in Fig. 6b that it is the ground surface that experiences maximum horizontal acceleration of 1.27 m/sec^2 equivalent to 0.129g or 0.535 times of the maximum applied horizontal acceleration (2.37 m/sec^2) whereas acceleration level experienced at the tunnel crown is only 0.90 m/sec^2.

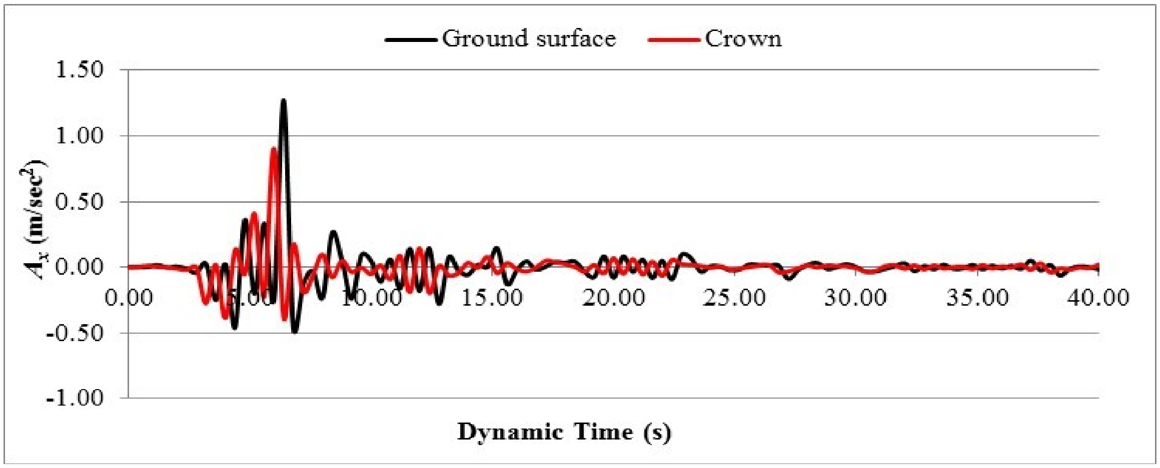

Fig. 6b - Time history of horizontal acceleration at different locations around tunnel Periphery due to 1991 Uttarkashi earthquake (horizontal component)

4.2 Response of soil-tunnel system to vertical component of acceleration

Vertical acceleration - time history, was applied to the base of the finite element model (Figs. 2 and 3) by applying prescribed displacements in vertical direction. Values of maximum residual settlements thus obtained are presented in Table 3. From Table 3, it can be noticed that residual displacements are found to increase after the occurrence of earthquake as compared to forces in static condition. The forces developed in RC liners are presented in Table 4 which shows that forces in RC liner increase for both earthquakes due to vertical component of earthquake. However, the increment is not significant.

Table 3 - Maximum residual displacements of tunnel and soil medium due to Vertical component

Maximum displacements (mm)	**Static**		**1999 Chamoli earthquake**		**1991 Uttarkashi earthquake**	
	Soil	**RC liners**	**Soil**	**RC liners**	**Soil**	**RC liners**
U_X	13.74	14.57	34.90	14.77	17.22	14.55
U_Y	25.60	26.94	41.85	17.69	42.60	43.95

Table 4 - Forces in RC liner due to vertical component of acceleration

Maximum forces in RC liner	**Static**	**1999 Chamoli earthquake**		**1991 Uttarkashi earthquake**	
		During shaking	**After shaking**	**During shaking**	**After shaking**
T (kN/m)	1030	1090	1040	1130	1030
V (kN/m)	176	188.98	177.99	199.83	175.60
M (kN-m/m)	269.66	289.38	272.71	305.91	269.06

The vertical acceleration-time history obtained at different locations in the medium due to vertical component of earthquakes has been presented in Figs. 7 a, b. For Chamoli earthquake, it can be noticed from Fig. 7a that maximum values of vertical acceleration are respectively 1.15 m/sec^2 and 0.563 m/sec^2 at the ground surface and at the crown. For Uttarkashi earthquake, it can be noticed from Fig. 7b that the corresponding values are respectively 1.52 m/sec^2 and 0.57 m/sec^2. It can therefore be inferred that the response of the system to vertical component of acceleration should also be paid attention during the design stage.

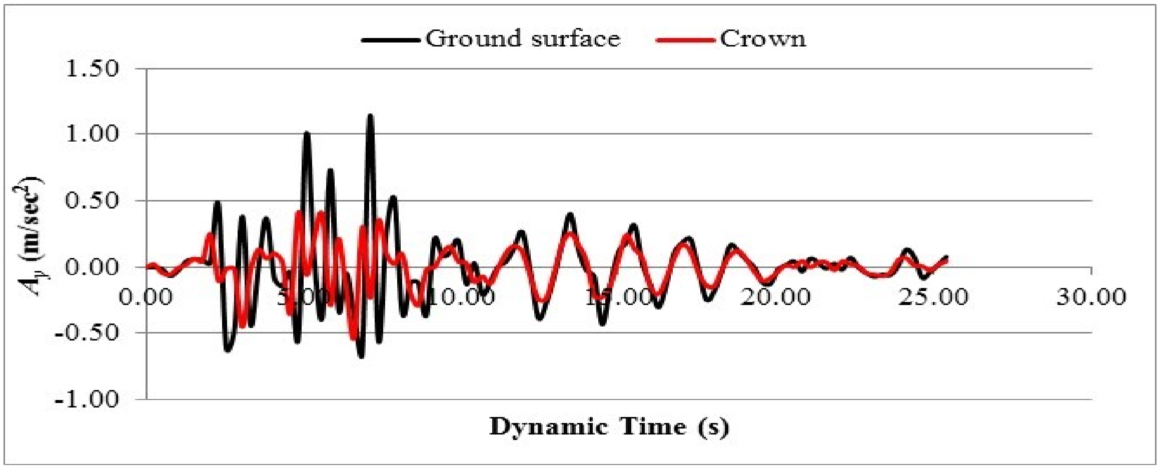

Fig. 7a - Vertical acceleration-time history at different locations due to 1999 Chamoli earthquake (vertical component)

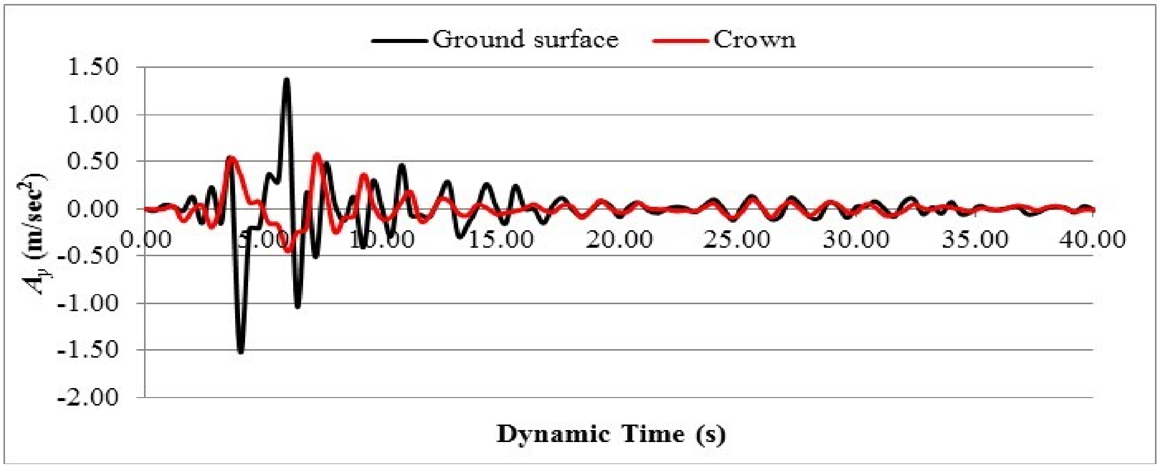

Fig. 7b - Vertical acceleration-time history at different locations due to 1991 Uttarkashi earthquake (vertical component)

5. Elastic vs. elastic-plastic analysis

Comparison between elastic response versus. elasto-plastic response has been presented in Table 5. A glance at this table suggests that maximum dynamic forces in RC liners decreases due to plasticity of soil mass, in case of both Chamoli and Uttarkashi earthquakes. Forces in RC liners have been found to reduce due to dissipation of earthquake energy through plastic points. Analysis also suggests that displacements in soil-tunnel system increase due to plasticity behaviour of soil medium. This is clear from Figs. 8a, 8b which show the time history of horizontal displacement at a typical point (springing point of tunnel) for Chamoli and Uttarkashi earthquake respectively. It can be seen that residual horizontal displacements increase due to plasticity of soil mass.

Table 5 -Comparison between elastic vs. elasto-plastic analysis based on dynamic forces

Dynamic forces in RC liners	**1999 Chamoli earthquake**		**1991 Uttarkashi earthquake**	
	Elastic analysis	**Elasto-plastic**	**Elastic analysis**	**Elasto-plastic**
δT *(kN/m)*	100	40	20	10
δV *(kN/m)*	130.74	53.95	52.33	8.01
δM *(kN-m/m)*	197.43	74.96	36.37	9.90

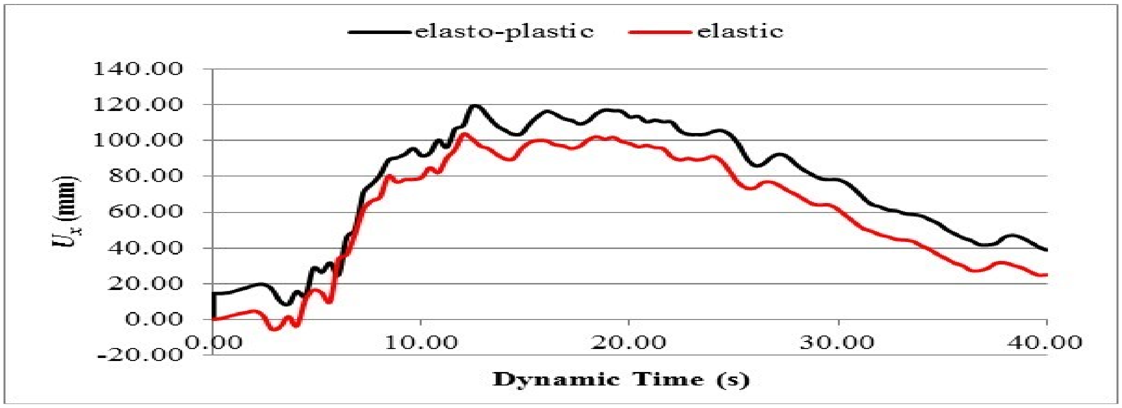

Fig. 8a - Time history of horizontal displacement (U_x) at springing point
(1991 Uttarkashi earthquake, horizontal component)

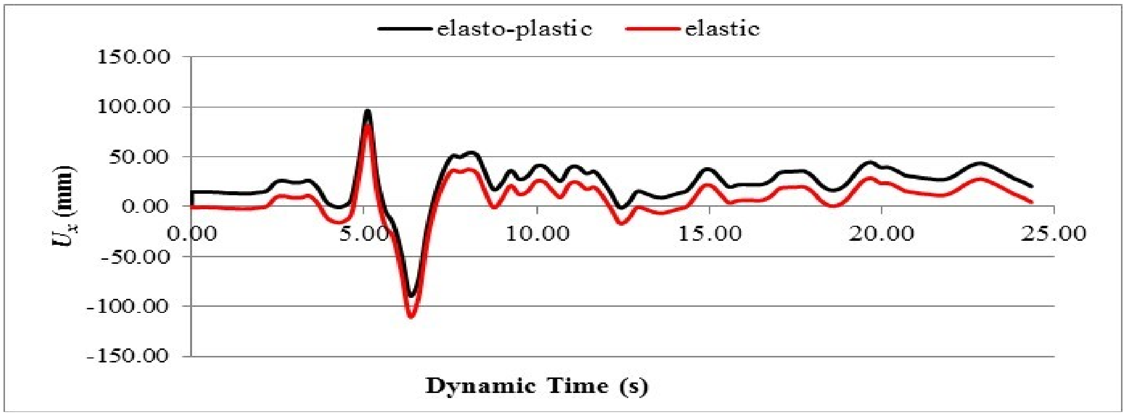

Fig. 8b - Time history of horizontal displacement (U_x) at springing point
(1999 Chamoli earthquake, horizontal component)

6. Conclusions

In this paper, attempt has been made to understand the seismic response of Delhi metro underground tunnels excavated in Delhi silt to 1999 Chamoli and 1991 Uttarkashi earthquakes. Elasto-plastic analysis has been carried out considering the Mohr Coulomb yield criterion. Results have been discussed in the form of displacement response, induced acceleration and forces in RC liners. Elasto-plastic response has been compared with the elastic response of soil mass. Based on such an analysis, following conclusions have been drawn:

i) Displacements and forces in RC liners of Delhi metro underground tunnels have been found to increase significantly due to application of horizontal component of both 1991 Uttarkashi and 1999 Chamoli earthquakes.

ii) Effect of horizontal component of both the earthquakes was more critical than the vertical component, though of course the influence of vertical component was also found to be significant. So, the seismic response to the vertical component of earthquake should also be considered for design.

iii) In general, maximum dynamic forces in RC liners have been found to decrease due to plasticity of soil mass, however, the residual displacements in soil-tunnel system have been found to increase due to plasticity.

iv) The present study therefore suggests that seismic analysis of shallow metro underground tunnels is essential and seismic influence must be given due consideration in design.

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