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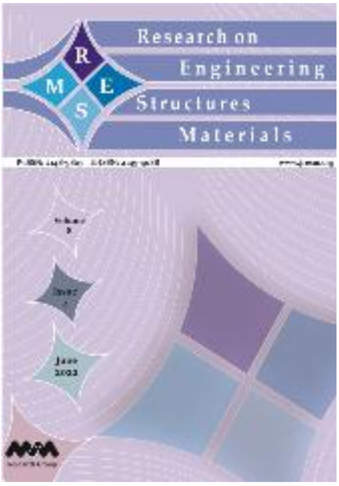

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Review Article

Evaluation of physical testing for seismic behaviour of tunnels: A comprehensive review

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Abstract

Underground structures are nowadays quite popular for urban construction. Since it is very difficult to begin post-damage construction immediately, the correct evaluation of its response during any seismic activity is an important factor for the analysis. Various physical models and numerical and analytical methods are recently introduced to study earthquake waves' effects on underground structures. This paper presents a brief review of the experimental tests, i.e., the Centrifuge test and Shake table test, used to analyze the performance of tunnels under a seismic environment with due consideration of the failure of the underground structure due to ground failure and ground shaking conditions. Besides this, the seismic behaviour of tunnels, factors influencing the behavior of tunnel structure and its failure patterns are also discussed. Subsequently, overall gaps in the study have been mentioned with the current understanding for its analysis.

1. Introduction

Tunnels are enclosed reinforced concrete RC structures used for transportation purposes and play an important role in the infrastructure of modern society. Tunnel serves a major purpose to cross water and mountain hindrance, and due to increased traffic in urban areas, metro tunnels also serve as the main loop to run trains on the busiest routes to shorten the time. The tunnel construction growth in the country has been driven by many projects, developing the urban-rapid-mass-transit systems, improving the connectivity between road, rail etc. To facilitate the needs of densely populated areas, tunnels are constructed at an increasing rate. According to the tunnel market survey 2019, the global tunneling market in India has nearly doubled as compared to 2016, with the main growth from road and rail tunnels (1). Being such an important part of the infrastructure, tunnels should be structurally stable and should be capable enough to resist static as well as dynamic loads imposed on them. Hence, an insightful study of the effects of the earthquake on the analysis, construction and design of tunnels is an important factor under consideration.

The major difference between the behaviour of surface structures and underground (UG) structures during an earthquake (EQ) is due to surrounding soil, which dominates the seismic design of underground structures (2–4), whereas the seismic behavior of surface structures is affected by the inertial forces. The contribution of soil-structure interaction is therefore, more in defining the seismic behaviour of underground structures.

On the basis of shape, tunnels are broadly classified as (5) (figure: 2).

- Mined or bored tunnels

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- Cut-cover tunnels
- Immersed tunnels

Bored tunnels are most popular where there are significant excavation depths and the presence of overlying structures. These are constructed using TBMs (Tunnel Boring Machines) or by drill and blast in rocks and thus are circular in shape. Cut and cover tunnels are constructed by means of excavating the soil, constructing the structure and then filling the surrounding of tunnel with the excavated soil. This method is employed for rectangular tunnel construction where excavation depth is shallow. Cut and cover tunnels are generally more economical up to a depth of 10m-12m than mined or bored tunnels. An immersed tube tunnel is an underwater tunnel constructed elsewhere and then floated to the site, sinked and anchored in place. These tunnels are used to cross water bodies where it is not suitable to construct a bridge or bored tunnels.

Earlier, no seismic effects were considered while designing the underground facilities, but, the consequences of various damages observed in the past, highlighted those underground structures which were not properly designed were subjected to vulnerable effects of the wave propagation. Failure of various tunnel structures and their behaviour within the seismic environment is discussed in this paper with details signifying the methods used for its analysis by various researchers and designers and subsequently describing the current gaps in their experimental testing.

2. Seismic Performance of Tunnels

Though underground structures are very less susceptible to EQ effects than above-ground structures; but, during several strong EQs like San Fernando EQ (1971), Northidge EQ (1994), and Kobe EQ (1995), various researchers documented the failures of underground structures. Dowding et. al.(5)observed 71 cases of damage of tunnels during a seismic event and concluded that most damage cases were observed in tunnels in rocks rather than tunnels in the soil. Owen G.N. et. al.(6) extended this study to 127 cases considering failures of cut and cover tunnels also as an addition to the data collected by (5). The prime factors for the failure of tunnels are increase in lateral forces arising due to surrounding soil backfill and duration of strong EQ.

Sharma et al. (7) updated the work of previous researchers by analyzing 192 cases of damage under 85 earthquakes and correlated the damage characteristics of tunnels to various parameters, namely tunnel geometry, geotechnical features and EQ characteristics like peak-ground acceleration (PGA), epicentral distance and magnitude. They concluded that deeper tunnels were less vulnerable to EQ damage as compared to shallow tunnels primarily due to the more confining pressure of the surrounding ground. Due to large embedment depth and overburden pressure the deformation in under-ground structures are very less as compared to surface structures. Besides this, as the distance of the structure from the epicenter increases the severity of damage decreases. Power M.S. et. al.(8) further investigated 217 cases of bored tunnels damaged after the Hyogoken-Nambu earthquake leading to failure of most underground structures. Daikai subway station is one of the prominent cases considered for evaluation of failure criteria of underground subway station. During the 1995 Kobe EQ, Daikai subway station located in Kobe, Japan suffered a collapse of ceiling slab and settlement of soil cover by 2.5 m as shown in figure 1.

Though there were various factors that prevented the collapse, which includes adding zig-zag reinforcement in addition to hoop reinforcement in the centre columns that did not buckle in comparison to columns with hoop reinforcement only(2). Also, the transverse walls at the ends act as shear walls and prevented the collapse(3).During Loma-Prieta EQ, structural cracking was observed in the tunnels and due to liquefaction of the surrounding soil, significant leakage was reported within the structure(3). Another example was observed during Chi-Chi EQ in Taiwan (Japan). Damage to the tunnel portals was due to slope instability, crack penetration, ground-water ingression, and collapse of lining, which leads to closing the entrance of tunnel at Chelungpu fault (figure: 3). One of the extensive damages caused during the 1999 Koceili EQ was the collapse of the twin Bolu tunnel. The left tunnel, which was still under construction during this period, suffered extensive damage (9). The major damage patterns observed were cracks and spalling of concrete lining, which might be due to tunnel crossing the fault.

(a)

(b)

Fig. 1 (a) Collapse of roadway overlying above Daikai subway station, (b) Collapse of central columns during Nyogoken- Nambu earthquake (1995) (3)

On the basis of the cases reported above, O'Rourke et. al. (10) classified the damage criteria of underground structures as:

- Ground shaking criteria
- Ground failure criteria

Ground shaking refers to the deformation produced by the shaking of the soil strata due to seismic waves propagating through it. Ground failure includes the failure of the surrounding soil like liquefaction, slope instability and fault displacement. The major factors influencing the dynamic behaviour of tunnels are tunnel geometry, ground conditions, the depth of the overburden and relative stiffness of the soil-tunnel interface etc., (3,7)(11–15).Most of the studies till now relate the damage criteria of tunnels during an earthquake to ground shaking, and very few have considered the damage due to failure of the ground (8,16,17). Chian and Madabhushi studied the effect of UG structures in liquefiable soil and concluded that lower unit weight of the tunnel structure as compared to the surrounding soil is the reason behind its vulnerability in liquefiable soil (16).

One of the major factors in the failure of the UG structure is the stresses generated in the lining (3,18,19). The past studies have considered the effect of the seismic environment under no-drainage conditions, Bobet analytically studied the effect of stresses induced in the tunnel-lining during an EQ considering the full-drainage and no-drainage conditions at the interface of the ground and the lining (20).Lining and ground were considered linearly elastic and plain-strain conditions were assumed at the cross-section of tunnel. The water table is assumed to be far from the tunnel hole and the effect of tunnel excavation on water table is neglected. To report the effect of water table, he considered 9 cases with different ground and liner stiffness. The results concluded that stresses in the tunnel lining are not affected by drainage conditions at the interface of ground and lining, if ground stresses are applied far from the centre of the tunnel, whereas the maximum stresses in the ground varies drastically. Sadiq et al. and Lu et al. (21,22) related the damage criteria to the flexibility ratio (F), which is defined as the relative stiffness of the structure to the soil. It has been observed that the F of the tunnel majorly influences the surface settlement and the deformation pattern. Stiff tunnels with F <1 show slight bulging at the surface, whereas the flexible tunnels with F>1 produce convex bending of both the roof and the floor slab (21). Singh and Mandal (23) studied the stresses induced in the tunnel considering different interface conditions with coefficient of friction varying as 0,0.4 and 3, considering the effect of overburden pressure and PGA were analyzed. For validation of the numerical model, the results of collapse of Daikai subway station were considered. With increasing PGA, the axial stresses in the tunnel central column increases for varying coefficient of friction and overburden-depth.

It was observed that axial stresses in tunnels central column were same for coefficient of friction as 0.4 and 3, with overburden depth of 6.34 m and 12.68 m. This is because of increase of inertial forces due to soil-amplification. Various factors considered by the researchers, which could probably affect the seismic behaviour of the UG structures to a greater extent are summarized in table:1. The performance of the tunnels is also affected by the structures present in their vicinity. A large amount of energy is released during the earthquake. This energy is carried by different waves produced during the seismic activity. The behavior of the UG structure is affected when these waves transfer this energy to the tunnel while passing through the tunnel section [18][24].

2.1. EQ Effects on UG Structure

Earthquake leads to the propagation of waves through the volume of the earth and crust, which causes the most damage (3). These waves are further classified as: Surface waves and Body waves. Underground structures are affected by the propagation of body waves, i.e., primary waves and secondary waves. Primary waves (P-waves) are the fastest of seismic waves and move the particles of the soil in the direction of propagation of waves by simultaneous push and pull that leads to alternate compression and tension. Secondary waves (S-waves) shake the particles up, down or side to side perpendicular to the direction of propagation of the wave.

On the basis of deformations, the EQ response of UG structures can be grouped as (6):

- Longitudinal bending
- Axial compression and extension
- Ovaling and Racking

Axial deformations are caused by the components of seismic waves, which produce motion parallel to the tunnel axis and cause alternate compression and tension. Hence it is said to be caused by the P- waves. Bending deformations are generated by the components of the wave propagating perpendicular to the longitudinal axis of the tunnel. Ovaling and racking deformations develop due to shear waves propagating normal to the tunnel axis, thus distorting the cross-sectional shape of the tunnel. figure: 5 describes the deformation patterns generally observed in the tunnel section due to the propagation of seismic waves through it. The characterization of different types of crack patterns observed in various cases can thus be due to different earthquake waves passing through the cross- section of the tunnel. On the basis of the propagating waves, design considerations for bending and axial deformations are provided in the direction parallel to the tunnel axis and in the transverse direction for the racking deformation (3).

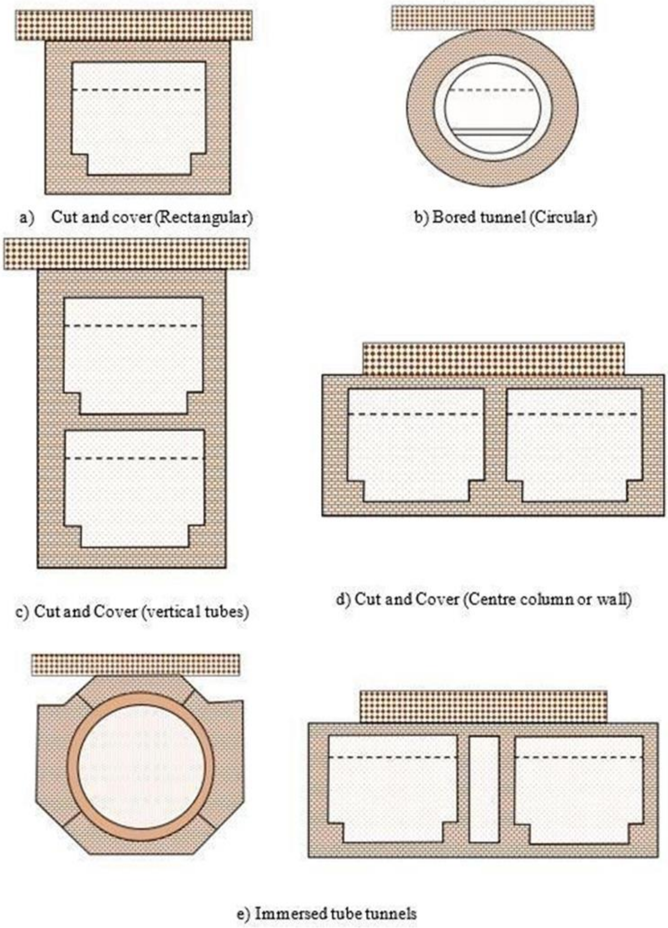
2.2. Seismic Analysis of Tunnels

The general method adopted in the seismic analysis of tunnels (12) (figure: 6) is broadly classified as:

- Free-Field Interaction approach (FFI)
- Dynamic Earth pressure approach
- Soil-Structure Interaction approach (SSI)

In FFI approach, the strains produced by a seismic wave propagating through the soil in the absence of the structure or excavation are considered while designing the tunnel, thus ignoring the effects of the interaction between the structure and the soil. A designer can impose these deformations directly on the structure(24,25). Though it is comparatively easy to formulate the results, it provides a conservative value if the structure is stiffer than the Ground and also provides less precise results for structure in variable ground conditions. San-Francisco BART subway station and LA metro were the structures designed with this approach and showed significantly good performance during the Loma Prieta Earthquake (1989) and Northridge Earthquake (1994), respectively.

Another approach used for the analysis of tunnel structures during EQ is the Dynamic Earth Pressure methods, which are based on the assumption that the inertial force of the surrounding soil is one of the criteria leading to its development. Mononobe-Okabe, given by Seed et al.(26) and the Japanese Society of Civil Engineering (27) is the widely used method for finding out the increase in the lateral earth pressure. This method was originally developed for retaining walls and considers that wall would move or tilt sufficiently so that an active earth yield wedge would form behind the wall. But for a UG structure, the structure and the surrounding ground move together, thus making it difficult for the yielding wedge to form.This method gives unrealistic results for the rectangular tunnel structures under plain-strain conditions and results in excessive shear deformations of the tunnel structure as compared to the surrounding soil. This effect becomes more prominent with the increase of depth of embedment because of reduction in deformation of structure and soil. Despite of all its shortcomings, this method is precisely applicable for tunnels with minimal soil-cover thickness.



a) Cut and cover (Rectangular)

b) Bored tunnel (Circular)

c) Cut and Cover (vertical tubes)

d) Cut and Cover (Centre column or wall)

e) Immersed tube tunnels

Fig. 2 Possible shapes of tunnels

Fig. 3 Tunnel portal failure due to slope instability after Chi-Chi earthquake(28)

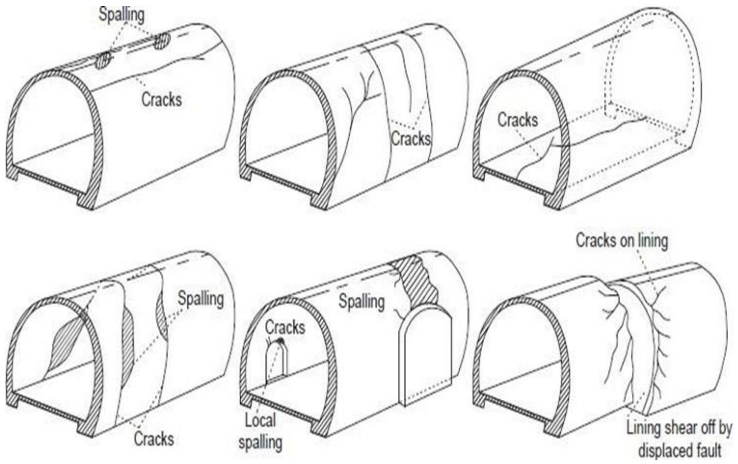
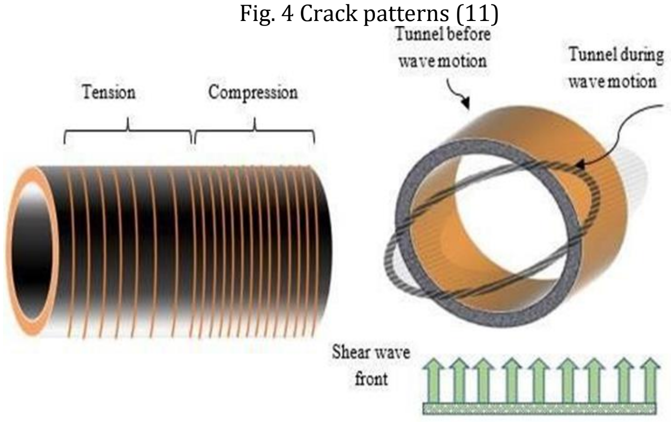
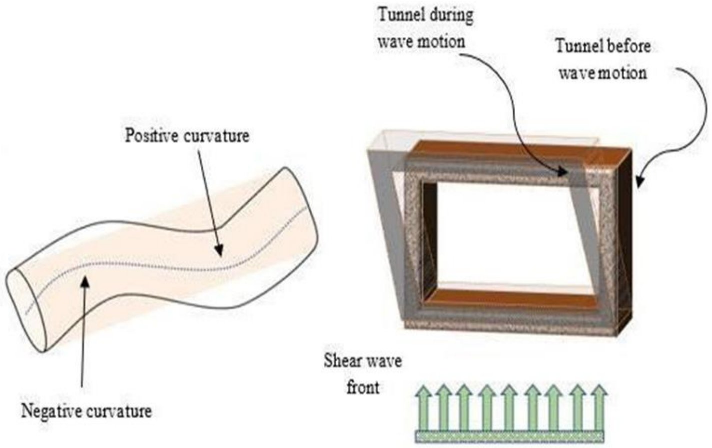


Fig. 4 Crack patterns (11)



a) Compression-extension b) Ovaling of tunnel section



c) Longitudinal bending d) Racking of tunnel section

Fig. 5 Various deformation modes of the underground structure subjected to seismic waves(redrawn and modified after (6)

Table 1**.** Factors influencing the seismic analysis of tunnels

Author	Factors affecting	Parameters considered
(16),(29–33)	Shape and dimensions of the tunnel	Soil and structure parameters
(13–16), (30,31,33,34)	Depth of overburden	
(29,31,33),(35)	Tunnel lining	
(12,13), (18,20,29),(30), (36–38)	Tunnel-soil interface	
(17,20)	Drainage conditions	
(13),(17),(29), (39)	PGA and PGV	Seismic and ground motion parameters
(40,41)	Frequency content	
(40)	Earthquake magnitude	
(38,39)	Intensity of earthquake	
(40)	Duration of earthquake	
(18), (33,34)		Effect of structures in vicinity

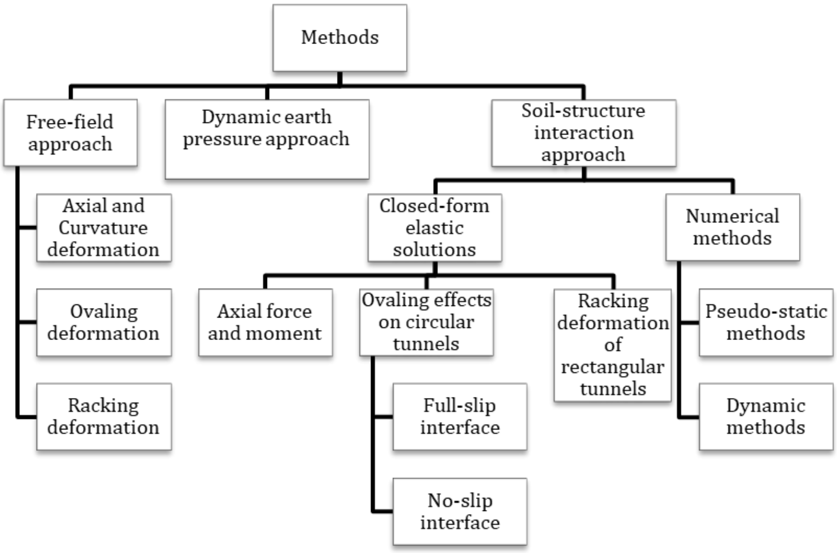


Fig. 6 Flow-chart representing methods of seismic analysis of tunnels

SSI considered the interaction between the structure and the soil, which is the major criteria affecting the seismic behavior of UG structures. Many researchers investigated the soil-structural response by various numerical and closed-form elastic solutions. The methods generally used comprise numerical dynamic analysis (21,42–47) frame-spring models (32,48,49) and subgrade reaction methods used to examine the seismic response of tunnel and the soil interface properties, the results of which can be validated through centrifuge testing.

3. Physical Testing of the EQ Response of Tunnels

3.1 Centrifuge Modelling

The actual behaviour of a tunnel structure can be verified by considering the "scaling effects," which are very difficult to consider fully in the laboratory. Centrifuge test is a reduced scale physical model which can apply the stress level that existed in the field to the prototype model (11).It is a widely used experimental set-up to examine the effects of both ground shaking and ground failure on the tunnel structure. The centrifuge applies an increased "gravitational" acceleration to the prototype model so as to produce stresses that are identical to the actual structure. The one-to-one scaling of stress increases the similarity of geotechnical models and makes it possible to obtain accurate data to help solve complex problems such as earthquake-induced liquefaction, soil-structure interaction etc. The basic mechanism of deformations induced and failure criteria can be well understood from this modeling technique. Further, it provides a useful benchmark for the verification of the numerical models. Earlier studies considered the effect of earth pressure and forces acting on the lining during shear deformation of the Ground to assess the damage induced in the tunnel (18),(35),(50). The later study mainly focused on the effect of vertically propagating transverse shear waves (35,51,52). Shibayama et al.(35) studied the effect of support conditions of tunnel lining on bending moment and axial forces induced during an EQ. For this purpose, he used two types of horse-shoe tunnel models to examine the effect of fixity conditions: for the first model, tunnel lining and invert were firmly fixed by welding, and for the second model, in order to transfer only axial force, the contact was modeled as a plastic hinge (non-welded). For tunnel lining to be rigidly fixed, the bending moment at the end of lining were quite large, whereas for lining to be rotational at the free end, the axial force at the shoulder end were high.

Kutter et al. (53) experimentally tested cut and cover tunnels by centrifuge modeling to understand the uplift mechanism and vulnerability during EQ-induced floatation. This study outlines the base to understanding the uplift behaviour of the tunnel during shaking, which is predominantly caused by the soil moving below the tunnel. The results reported a total uplift of 180 mm, which is verified by a numerical model with an error of 20%. The error could arise due to pore pressure generation, liquefaction and large strains in base course soil etc. Post-shaking uplift was also observed to be found as 30 mm in centrifuge testing and 5 mm with numerical testing. Chian et. al. (16) carries out their investigation on Ground susceptible to liquefaction during an earthquake, thus causing an uplift of the structure due to its lower unit weight as compared to the surrounding Ground. The depth of burial of the structure and its size are the major factors influencing the uplift behaviour of the structure. This could be due to increased resisting forces due to increased vertical earth pressure and inertial forces of the structure which resist the buoyant forces due to liquefied surrounding soil.

Chou et al. (17) continuing the previous research on the uplift performance of the tunnels consolidated the results by providing mechanisms observed during the uplift, i.e., the ratcheting mechanism in which the sand migrates underneath the tunnel with every cycle of relative shaking, pore-water mechanism and bottom-heave mechanism. Though, the fourth mechanism, i.e., viscous flow of liquefied soil, was not observed in these experimental results. Table: 2 provides a summary of the tests carried out by various researchers in the past and shows that very less work has been carried out till now for understanding the behaviour of tunnels in ground failure conditions. Since EQ-induced flotation failure has a great potential for loss of economy and life, methods to reduce its impact must be studied in detail for further study. One way to reduce the impact of flotation failure is the improvement of the ground; Taylor et al. (54) studied the use of coarse-grained granular backfill around the tunnel by replacing areas of liquefiable soil and observed that ground improvement done below the tunnel was most effective in reducing the uplift of the structure.

Depth, shape, tunnel lining stiffness, nature of input motion and properties of surrounding soil strata affect the behaviour of the tunnel during an earthquake. Dynamic centrifuge experimentally evaluates these factors at different input ground motions with varying frequencies and amplitude. Cilingir et al. (14,40,55) studied the effect of the input motion on the seismic behaviour of both square and circular tunnels, which is influenced mostly by the intensity of the earthquake, peak ground velocity (PGV) and peak ground acceleration (PGA) value and are least influenced by the duration and frequency content. In this study, they experimentally observed three stages of failure: the transient stage, steady-state cyclic stage and residual stage. The tunnel structure reaches a dynamic equilibrium stage in the first few cycles; in the second stage, the earth pressure values get stagnant about a particular value and this oscillating value gets fixed during the third stage when the shaking stops.

Chen et al. (56) discussed various methods proposed for the seismic protection of tunnels. The isolation layer is generally used to protect the tunnels crossing different soil strata as it absorbs the deformations of the Ground that are caused by an EQ and thus, reduces the cross-sectional deformation of the tunnel cross-section, further reducing the dynamic bending moment. Chian and Madabhushi (15) observed that when the shaking of the model was gradually decreased to 40g, there was a decrease in the internal forces, which suggests that due to lowering confining stress, the sand dilates instead of contracting and hence, the lining recovers a part of the accumulated strain.

Chen et al. (56) evaluated the results of the effect of the presence of an isolation layer for a frequency of 50 Hz, and as shown in figure: 7, the dynamic bending moment at corners are much larger than those at other location and therefore, the corners of a rectangular tunnel are to be designed with proper seismic considerations. Presence of isolation layer reduces the moments at the corners, thus providing structural safety under seismic loading.The rectangular tunnel structure is more profound to show a rocking-racking deformation behaviour under transversal Ground shaking. This combined behaviour was verified by various centrifuge tests, in which a rigid tunnel is subjected to more rocking deformation with reduced racking, whereas flexible tunnels show prominent racking values and less rocking deformations. Since, racking deformation amplifies with flexibility of the structure, flexible tunnels are more prone to racking failure than rocking failure. Tsinidis et al. (30) verified these results by conducting a centrifuge test on rectangular tunnel structures and the results have been evaluated in terms of the relative flexibility of soil-tunnel and soil-structure interface properties. Table 3 gives the values of the dynamic bending moment for rigid and flexible tunnel structures, and it has been observed that dynamic bending moment values are higher for rigid tunnels as compared to flexible tunnels.

Till now, most of the tests examined the behaviour of the underground structures without considering the structures in the vicinity. But ideally, the presence of other structures in their vicinity also influences their behaviour during an earthquake. Though very few studies have been carried out recently and are still undergoing investigation of the effects of nearby structures (could be another tunnel, above-ground structures like buildings etc.). Gillis et al.(18,57) studied the effect of the presence of temporary and permanent structures in the vicinity of a mid to high-rise building and study the effect in terms of inertial force of tall buildings, added confinement of the building and constraints added on the foundation. The added confinement by high-rise structures reduces the racking deformation of the structure but also, increases the lateral earth pressure. Particularly, they examined the results of seismic environment on isolated cut and cover structures, temporary excavation and the presence of mid to high-rise buildings in its locality. Hashash et al. (58), using centrifuge modeling, implied that interaction between the building and the tunnel can majorly influence the seismic behaviour of cut and cover tunnels.

Various observations from centrifuge modeling give extremely useful results in examining the behaviour of tunnel structures, but there is certain limitation this method portrays in modeling minor details of the section and special components like joints between different segments of the lining. Further, to model the lining of the tunnel, the material used is often aluminium which poses the effect on the recorded response.

3.2 Shake Table Test (STT)

STT was invented in 1893 by the University of Tokyo and had a major application for the seismic analysis of above-ground structures. But for a few decades, it has been significantly used for the UG structures. It may be used as an alternative to the centrifuge test with the advantage of modeling much larger models in size and the use of more realistic materials for the tunnel lining. The shortcomings of plain concrete that need special attention are its low tensile strength and brittle behavior (59).To overcome this, various material has been proposed as the tunnel lining like rubber sheet lining (13), plexiglass (22), polypropylene fibre reinforced concrete (59), ultra-high-performance fibre reinforced concrete (60),using gypsum and water slurry (61), concrete lining (62), steel reinforced concrete lining, organic glass (63) and steel fiber concrete and steel-basalt fiber reinforced concrete lining (64).

Various tests have been carried out on decoding the parameters influencing the EQ response of the tunnel structures in different soil conditions. But very few studies have been carried out to investigate its behaviour into two different stratum. Liang et al. (62) proposed a similitude-ratio method to analyze the behaviour of circular tunnels under soft-hard soil stratum with a shake table test. This test is depended on the size of the laminar shear box, performance parameters of the shake-table, and the material characteristics of the model tunnel. The tunnel strain around the soft-hard interface increases significantly, which could be due to a change of relative stiffness at the junction of the soft-hard medium. Because of the different dynamic characteristics of the structures, the behavior of seismic waves will be different and thus, at the point of intersection the coherence between these waves decides the seismic performance of the tunnel. Zhang et al. (67) analyzed the behaviour of shaft-tunnel junction showing discrepant responses causing the bending deformation of the tunnel axis and enlargement of the strains at the junction. These additional strains are generally imposed on the shafts. Also, at the junction of the shaft and the tunnel, the longitudinal circumferential-joint extensions and the transverse dynamic strains are raised. This observation constitutes additional evidence of the damage to the tunnel.

Consideration of the uniform wave excitation has been carried out so far to analyze the behaviour of the tunnel, but Chen et al. (13) carried out the first STT on the tunnel under non-uniform excitation to examine the performance of rectangular tunnel with and without construction joints. The actual behaviour of the tunnel is very difficult to account for in the laboratory due to the "scale effects" (11). Though centrifuge modeling provides a compatible way to model scale effects; but, due to its limitation of modeling structures with larger dimensions because of size limitations, it is necessary to consider the issue for further investigation. Using a synthetic soil model (i.e., a mixture of sand and saw-dust) has been found to be a remedy to the scaling issues (68).

The isolation layer provides one of the effective methods used for reducing the dynamic earth pressure effects on the lining. It minimizes the intensity of seismic action and reduces the deformation transferred from ground to the tunnel lining (42). Xu et al. (61) using a shake table test, investigated the effect of using geofoam as a seismic isolation layer between the rock and the tunnel lining. The results interpreted show that installation of a geofoam isolation layer reduces the dynamic earth pressure by 70-90% in comparison to cases without an isolation layer. The effects of reinforcing the rock with anchors, adding of steel wire mesh layer in the lining and provision of flexible joints in the tunnel lining were some other areas of research investigated in this study. Results revealed that provision of anchor reinforcement reduces the dynamic strain in the lining by 50 % to 60 %, as compared to non-anchored structure. These methods were found effective in dissipating the earthquake energy and thus, reduces the dynamic strain in the tunnel.

Table 2. Summary of experimental test results

Method	**Author**	**Cross-section of tunnel**			**Ground Shaking**	**Ground Failure**	**Racking /Ovaling deformation**	**Rocking deformation**	**Uplift displacement/Floatation**
		Rectangular	**Circular**	**Other**					
Dynamic Centrifuge test	(53)	✓				✓	✓		
	(17)	✓				✓			✓
	(40)	✓	✓		✓		✓		
	(16)		✓			✓	✓		✓
	(15)		✓				✓		
	(38,65)	✓					✓	✓	
	(18)	✓					✓		
	(66)	✓					✓		
Shake Table test	(41)	✓					✓		
	(34)	✓					✓		
	(67)		✓				✓		
	(68)	✓					✓		
	(54)			✓		✓			✓
	(69)			✓			✓		
	(70)		✓			✓			✓
	(71)			✓			✓		

Some studies have contributed to study the effect of tunnels in liquefiable ground using shake-table testing (70,72), crossing faults (73)(74), effect of flexibility ratio (22) . Tsinidis et al. studies the effect of heavy buildings on the response of single or twin circular tunnels in the urban environment and signifies that the number of single-degree-of-freedom of the building and their position relative to an axis of tunnel majorly affects the seismic performance of the tunnel structure (34). Singh et. al.(75) studied the seismic behavior of tunnels damaged during aftershocks and concluded that damaged tunnels are more vulnerable to low-frequency earthquake motion. The effect of after-shocks on damage characteristics of tunnels is still required to be studied in detail. One of the limitations of the shake table test was a little study on the similitude laws to study the post- cracking behaviour of the tunnel lining (69). Antoniou et al. (69) proposed scaling laws for the 1 g shake table test, simulating the post-cracking phase of lightly reinforced concrete lining found in rock, but still, much work has to be done on this. Increased scaling laws allow for investigating the urban conditions more easily and precisely in comparison to centrifuge tests. But this 1-g test is performed at confining stress much lower than in the field; therefore, there is a difference in the recorded response and the actual one; thus, the actual condition in the field is not accurately represented. Shake table tests are, therefore, of less importance for verification and validation of the numerical and analytical methods.

Table 3. Effect of the soil-tunnel interface properties and soil non-linear response on the dynamic lining bending moment (N-mm/mm) (38)

Considered points	Flexible-elastic		Flexible-elastoplastic		Rigid-elastic		Rigid-elastoplastic	
	No-slip	Full-slip	No-slip	Full-slip	No-slip	Full-slip	No-slip	Full-slip
A	-4.871	-2.367	-6.294	-2.282	-10.946	-3.564	-6.27	-2.203
B	6.54	3.303	4.268	0.45	11.481	3.117	10.10	0.426
C	-5.524	-3.772	-5.235	0.154	-10.88	-3.974	-7.568	-1.757
D	5.596	4.358	4.084	-0.366	12.307	4.371	8.973	1.135
A	-4.784	-2.936	-3.563	0.403	-10.759	-3.859	-8.336	-1.243

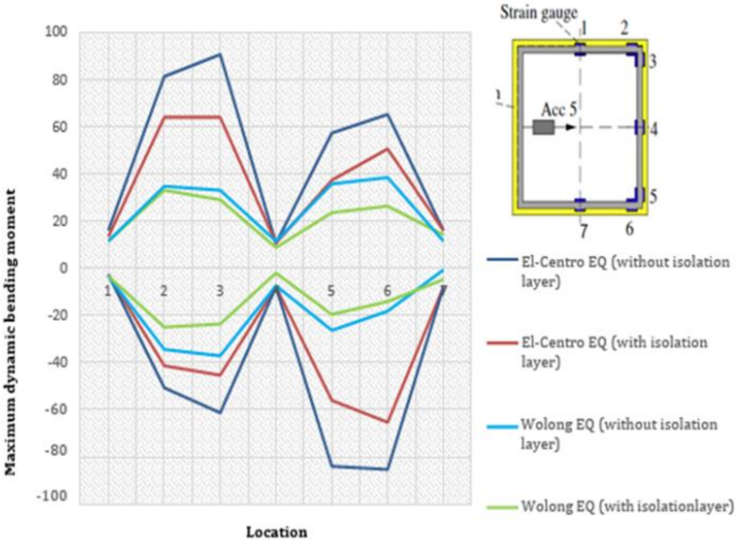


Fig. 7 Impact of isolation layer on Dynamic Bending Moment (56)

3. Conclusions and Recommendations

With the detailed study of the seismic environment on the performance characteristics of tunnels, the following conclusions can be made regarding their experimental testing:

- Major contributors to seismic response in tunnels are PGA, PGV, EQ intensity, shape and cross-section of the tunnel, interface properties and presence of another structure.
- Monobe-Okabe method of does not give realistic values for rectangular tunnels and proposes much higher racking values in comparison to the encircling soil. Still, this method is suitable for tunnels with minimum soil cover.
- Corners of a rectangular tunnel develop maximum values of bending moment during an EQ, so joints should be designed with precision, but the presence of an isolation layer helps in reducing these values to some extent.
- Stiff rectangular tunnels tend to show bulging at the surface during deformation, whereas flexible tunnels show convex bending of both roof and floor slabs.
- Tunnels subjected to an environment with multi-stiffness characteristics (for example, the presence of structures in the surrounding or tunnel passing through soil with varying stiffness) show an increase in strain values at the joints. This could be due to the coherence between the waves propagating through different media.
- Centrifuge test, due to its inability to model buildings with high-fundamental frequency, resulted in studying the limited factors for structures in the vicinity of tunnels, whereas STT provides an easier way to model the structure at a larger scale but is of less importance to validation of numerical models.

This paper presented a brief review of the current approaches to experimentally understand the behaviour and performance of tunnels under an EQ. Based on it, further work that needs to be considered are:

- Experimental tests studied considers the uni-directional horizontal ground motions, but in the actual scenario, the motions are three-dimensional. So, instrumentation of tunnels under three- dimensional shaking conditions in order to measure both lateral and vertical response of the structure must be evaluated.
- The performance of tunnels has been evaluated for the simplistic soil conditions. Few recent studies have considered different soil-strata conditions and the effect of varying stiffness of the surrounding soil, but still, a detailed study to investigate the effect of non-linearity of soil on EQ performance of tunnels needs to be studied.
- The inelastic response of the tunnel lining needs to be considered for further work.
- The old tunnels are prone to the aging effects of lining, which affects their performance during seismic response. In order to develop cost-efficient retrofitting techniques and studying the residual life of existing old tunnels, further work needs to be carried out.
- Study of the influence of different isolation material in reducing the bending moment induced in a tunnel so as to maintain its structural integrity should be evaluated, in order to have a cost- efficient material for practical application.

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