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Research Paper

Seismic study of shallow circular tunnel in Red River sand (Vietnam)

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ABSTRACT

Attention should be paid to tunnels' seismic behaviour since many of them have been damaged by earthquakes. The paper presented a seismic study of a shallow circular tunnel by physical modelling on shaking table test. A small scale tunnel model of the Hanoi pilot metro line's underground segment was placed in the middle of a rigid soil container and buried in Red River sand (Vietnam). The table was vibrated along the soil container's long wall, with a simulated seismic wave created from the 1788 Tolmezzo (Italia) accelerogram. Five testing campaigns were executed, and the model's acceleration data were studied. The uni-directional vibration created by the shaking table caused the three-directional vibration of the physical model. The Fast Fourier Transform (FFT) frequency spectrum analyses were performed. The vibration characteristics of the model (i.e., frequency graph's structure, maximal acceleration, dominant frequency, strong-motion duration) in three orthogonal directions under the artificial earthquake action were compared. The obtained results proved the complicated seismic impacts on a shallow tunnel.

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1 Introduction

The tunnels are normally less affected by earthquakes than the surfaced and elevated structures [1]. However, their failures in such situations have been witnessed. H.R. Pratt et al. listed 29 tunnel damage cases under six earthquakes from 1906 to 1952 [2]. In statistical research by P. Spyridis and D. Proske in 2021, 6% of 321 tunnels and undergrounds were damaged by the earthquake [3]. Studying 81 mountain tunnels, Z. Cheng et al. have classified six typical seismic structural damages: lining cracks, shear failure of lining, tunnel collapse by slope failure, portal cracking, leaking, and deformation of the sidewall or invert damage [4].

Earthquakes cause two impacts on tunnel structures: ground shaking and ground failure [1]. The seismic bearing characteristics of tunnels are complicated since they are affected by various factors. C.H. Dowding and A. Rzen in 1978 ranked three tunnel damage levels depended on the amplitude of peak ground velocity (PGV): Nil when PGV<0.2m/s, minor

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when $0.2 < PGV < 0.9 \text{ m/s}$, evident when $PGV > 0.9 \text{ m/s}$ [5]. The surrounding environment also takes an impact: The soil tunnels are more vulnerable than the rock ones [1]. Besides, shallow-buried structures seem less safe than the deeper ones: The ground motion at the tunnel's depth reduces contrarily to the tunnel's depth [1, 6].

In seismology, the physical modelling of structure is prepared for various experimental tests. Among different techniques for tunnels under seismic loading, the two most popular dynamic solutions are shaking table and centrifuge: The former for 1-g models and the latter for high-g ones. Due to the size limitation of the testing machines, the models are often small scale using the complete structuring methods or large scale using sub-structuring ones. In Vietnam, two shaking tables are currently available for research studies: a $3 \times 3 \text{ m}$ at the Vietnam Institute for Building sciences and technology (IBST) and a $2 \times 2 \text{ m}$ at the University of Transport and Communications (UTC). They have been used for dynamic studies of partial structures of buildings and bridges.

The earthquake probability in Hanoi and its boundary is high (up to VII – IX degrees in MSK-64) [7]. Besides, Hanoi's location on the Red River fault has the potential to pose a seismic hazard to the city. The Red River is the biggest river that runs across Hanoi and the northern area of Vietnam. Red River sand is a natural fine to medium-sized loose material. It is in the shallow layers of the riverbed and the ground of many areas in Hanoi and its surroundings. Since 2009, the construction of the pilot metro line (Line 3) in Hanoi has been started. While the elevated part of the line was finished, the 4km tunnel part will soon be bored by TBM technology. With the predicted peak ground acceleration $PGA = 0.11g$, the seismic action was calculated by the pseudo-static method in the design documents, and a favourable seismic condition for the line was concluded. Besides, C.T Nguyen et al. had several seismic theoretical and numerical research on the line [8, 9]. A research project using the shaking table techniques for a tunnel buried in the Red River sand has arisen in UTC under such circumstances. The experimental study aimed to demonstrate the earthquake's impacts on tunnels.

2 Seismic study by shaking table

The tunnel part of the Hanoi metro Line 3 was the prototype for creating a hypothetical study case. Taking notice of the dimension and loading capacity of the UTC's shaking table, the geometrical similarity study was performed, and the 1:21 geometrical scale was chosen. The most unfavourable overburden height when it was equal to the tunnel's diameter was selected. Since the ground conditions along Line 3 were diversified, we chose the simplest case for the ground modelling when the tunnel was covered only by Red River sand. The obtained physical model was a tunnel model staying in the middle of the rigid soil container filled with the homogeneous Red River sand (see Fig.1 and Table 1).

Table 1 – Parameters of the physical model.

Component	Parameter	Information
Tunnel model	Outer diameter	0.30m
	Inner diameter	0.27m
	Length	1.00m
	Material	Finer grain concrete
Soil container	Type	Rigid wall
	Length	1.80m
	Width	1.60m
	Height	1.20m
Simulated ground	Filling material	Homogeneous Red River sand
	Height	0.90m

The geotechnical of Red River sand used in the model was presented in Table 2.

Table 2 – Geotechnical parameters of Red River sand in the physical model.

Parameter	Value
Specific weight	2.66g/cm ³
Angle of repose	22 ÷ 34 degrees
Void ratio	0.75 ÷ 1.26
Moisture content	15.48%

The accelerogram of the 1788 Tolmezzo (Italia) earthquake was chosen to create the simulated seismic wave for the study (see Fig. 2). It was chosen because its response spectrum was adapted to requirements of the Vietnamese specifications TCVN 9386:2012 [10]. Moreover, its characteristics (length, intensity) were suitable for the shaking table and the experimental conditions in the UTC laboratory. It was used as the input data for controlling the vibration of the shaking table. The shaking table vibrated along the long wall, perpendicular to the short wall of the soil container. Five testing campaigns were performed with 25%, 55%, 75%, 85%, and 100% values of the accelerogram.

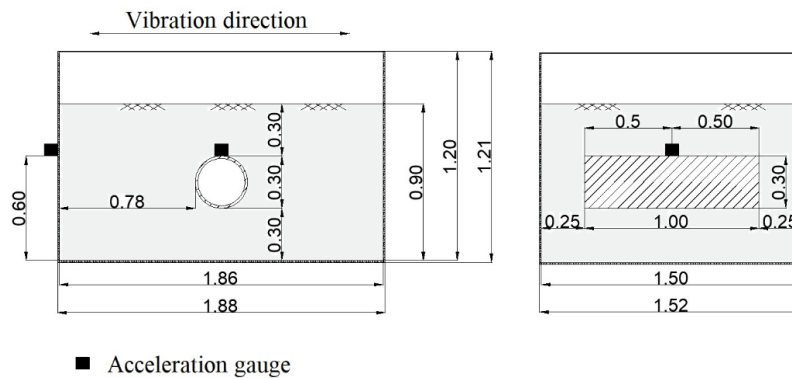


Fig. 1 – Geometrical parameters of the physical model.

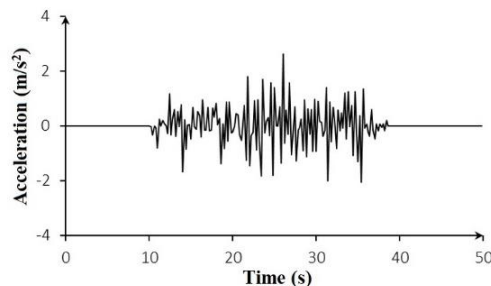


Fig. 2 – Accelerogram of the simulated seismic wave.

The acceleration gauges were arranged at different locations in the physical model. In the scope of this paper, the obtained data at two specific locations were studied: Container's wall and Tunnel model (see Fig. 1).

3 Results and discussions

The acceleration data at two locations during five testing campaigns were collected. Once the accelerograms were sketched, their shapes and structures were analysed. The Fast Fourier Transform (FFT) frequency spectrum analyses by MATLAB were performed to understand the physical model's vibration characteristics, and the vibrations' typical features were collected. In the following parts, detailed works were shown.

3.1 Longitudinal vibration

The longitudinal vibration of the physical model was studied through the obtained acceleration values along the soil container's long wall. Each pair of data on the soil container's wall and on the tunnel model in a testing campaign were compared. The accelerograms at the 100% value testing campaign were shown in Fig. 3 as the representative of all the testing campaigns.

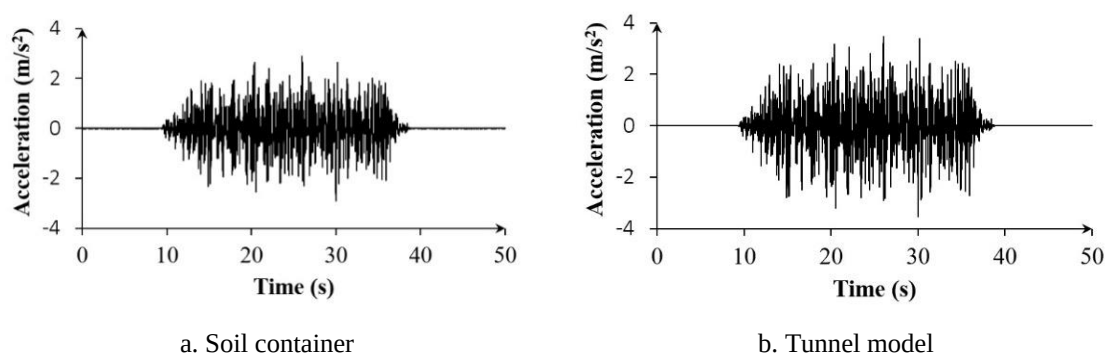


Fig. 3 – Accelerogram of the simulated seismic wave.

It was found that the shape and structure of the accelerograms were similar, and the existence period of the signal was concurrence. The structures of their frequency graphs resulting from the FFT frequency spectrum analysis were identical. The seismic vibration properties were presented in Table 3, and the frequency graphs of the 100% value testing campaign were shown in Fig. 4 as the representative of all testing campaigns.

Table 3 – Seismic vibration properties of the soil container and tunnel model in the longitudinal direction.

Testing campaign	Component	PGA (m/s^2)	Dominant frequency (Hz)	Strong-motion duration (s)	Percentage of strong-motion (%)
25%	Soil container	0.77	7.75	27.58	35.12
	Tunnel model	0.90	7.75	27.78	38.88
55%	Soil container	1.59	7.75	28.86	47.51
	Tunnel model	1.90	7.75	28.85	48.82
75%	Soil container	2.25	7.75	28.87	51.11
	Tunnel model	2.71	7.75	28.87	52.39
85%	Soil container	2.48	7.75	28.88	51.88
	Tunnel model	3.02	7.75	28.87	53.09
100%	Soil container	2.90	7.75	28.91	52.68
	Tunnel model	3.56	7.75	28.92	54.02

In Table 3, the “strong-motion” was taken as the acceleration amplitude not smaller than 0.05g, and the “strong-motion duration” was the interval between the first and the last strong-motion signals after the ideas of R.A. Page et al. [11].

The effect of the simulated ground on the tunnel model was explained by the differences between the two mentioned accelerograms. The acceleration measured on the tunnel model was considered the accumulation of the acceleration created by the shaking table and the simulated ground. In this study, the ground's accelerogram was obtained by subtracting the soil container's graph from the tunnel model's graph. The results were presented in Table 4.

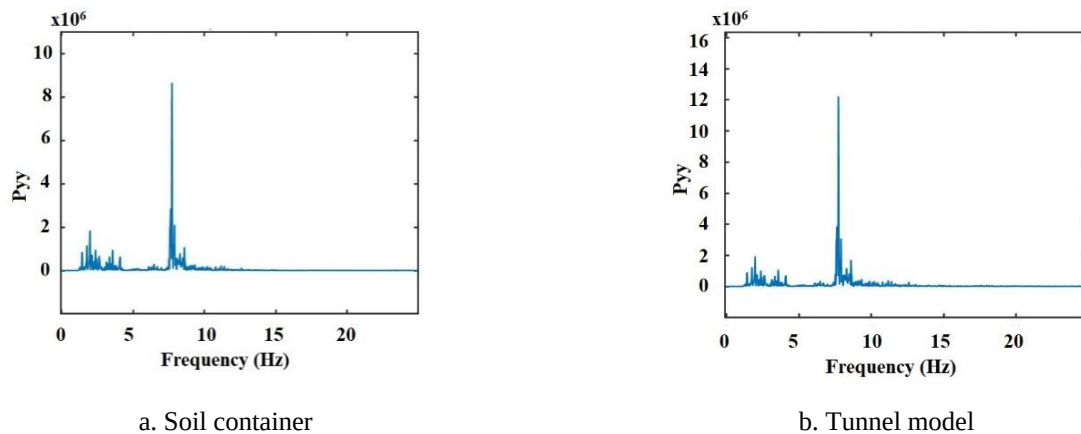


Fig. 4 – Frequency graph of the 100% value testing campaign.

Table 4 – Seismic vibration properties of the simulated ground in the longitudinal direction.

Testing campaign	PGA (m/s^2)	Dominant frequency (Hz)	Strong-motion duration (s)	Percentage of strong-motion (%)
25%	0.32	7.75	26.14	6.52
55%	0.69	7.75	28.18	23.61
75%	1.30	7.75	28.21	33.07
85%	1.58	7.75	28.26	35.68
100%	2.19	7.75	28.32	39.79

The dominant frequencies of all components during all testing campaigns were always 7.75Hz, and the structure of the frequency graphs was similar. It was understood that the seismic vibration at all model components was the same, with some small diversities of the power spectral density values. The FFT results showed that all components of the physical model were simultaneously vibrated without relative displacements. The rigidity of the soil container caused no effects on the free movements of the other components.

3.2 Horizontal and vertical vibration

The three-directional vibration of the soil container was investigated. Although the shaking table had been controlled to vibrate only in one direction, the three directional acceleration data at the soil container's wall were captured (see Fig. 5).

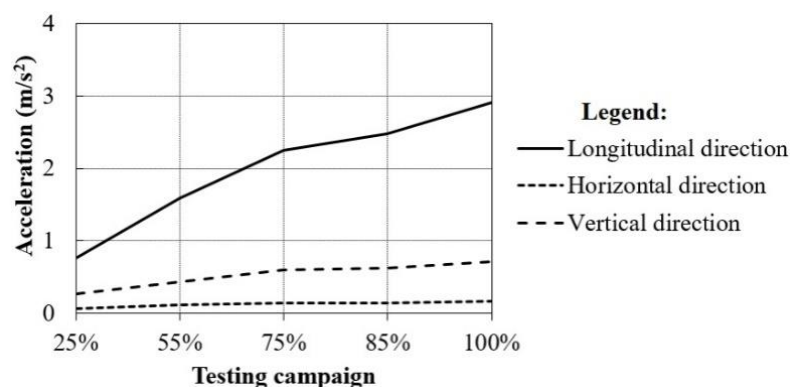


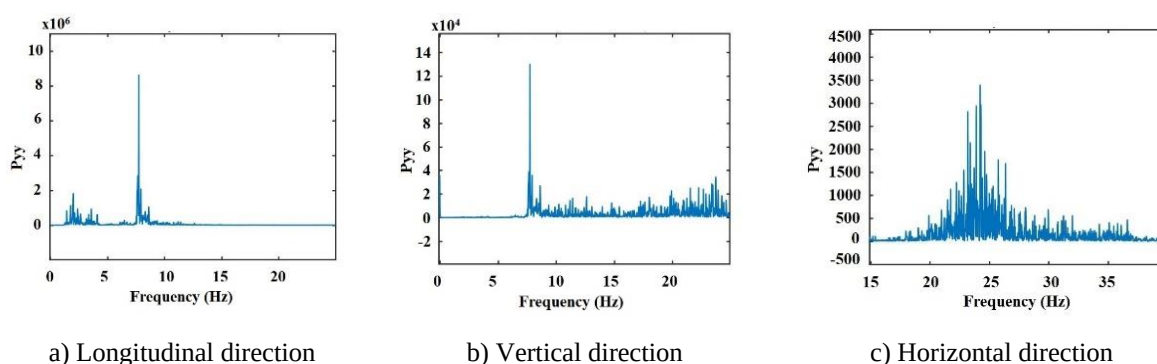
Fig. 5 – Three-directional PGA measured on the soil container.

The PGA proportion values between the vibrations in three directions of the soil container were shown in Table 5.

Table 5 – PGA proportions between three direction seismic vibrations of the soil container.

Testing campaign	Horizontal versus longitudinal direction	Horizontal versus vertical direction	Vertical versus longitudinal direction
25%	8.87%	25.52%	34.78%
55%	7.13%	26.44%	26.98%
75%	6.54%	24.45%	26.73%
85%	5.94%	23.55%	25.24%
100%	5.85%	24.05%	24.31%

Some remarks were found when the vibration characteristics in three directions were compared. Among three directions, the vibration along the longitudinal direction prevailed. The shape and structure of the accelerograms in three directions were similar. However, the shape and structure of the frequency graphs in three directions from FFT spectrum analysis were diverse. The frequency graphs of the 100% value testing campaign were presented in Fig. 6 as the representative of all testing campaigns.

**Fig. 6 – Frequency graphs of the 100% value testing campaign.**

Despite the same value of the dominant frequency (7.75Hz), the distribution tendency of the frequencies with notable amplitudes on the frequency graphs of the vertical vibration was different from that of the longitudinal one. The dominant frequencies of the horizontal vibration were around three times larger than the values of two other vibrations, and the amplitudes of the former were much higher than those of the latter. The strong-motion duration of the vertical and longitudinal vibrations was similar, while the strong-motion duration of the horizontal vibrations was the shortest.

4 Conclusions

The paper presented an experimental study on a small scale physical model of the Hanoi pilot metro line's underground segment in UTC (Hanoi campus). The 1:21 geometrical scale was chosen, and the simulated seismic created from the 1788 Tolmezzo (Italia) earthquake was used for the shaking table. The obtained accelerations at the soil container's wall and the tunnel model were studied. The data and FFT frequency spectrum analyses were performed to understand the vibration characteristics of the physical model. The complicated seismic impacts on the tunnel model were confirmed when the uni-directional simulated seismic wave created the three-directional vibration to the physical model with the heterogeneous vibration characteristics. At the soil container, the vibration in the vertical and horizontal directions also arose beside the longitudinal vibration created by the shaking table. The PGA of the vertical vibration was around 30%, while the PGA of the horizontal vibration was smaller than 10% of the longitudinal vibration. Moreover, in the same vibration condition, the acceleration of the tunnel model was always higher than the one of the soil container. The fact was explained as the accumulated effect of the shaking table and the simulated soil on the tunnel model.

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