Tunnelling and Underground Space Technology 59 (2016) 199–214

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

# Seismic response of box-type tunnels in soft soil: Experimental and numerical investigation

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ARTICLE INFO

*Article history:*
Received 14 January 2016
Received in revised form 14 May 2016
Accepted 14 July 2016

*Keywords:*
Box-type tunnels
Dynamic centrifuge testing
Dynamic analysis
Simplified analysis methods

ABSTRACT

A series of dynamic centrifuge tests were carried out at the geotechnical centrifuge facility of IFSTTAR in Nantes, to investigate the response of box-type tunnels embedded in dry sand under sinusoidal and seismic excitation, as affected by soil-tunnel relative flexibility and soil-structure interface rugosity. The system under investigation was analyzed by means of full dynamic time history analyses, implementing rigorous finite element models. The numerical models were calibrated on the basis of back analysis of tests, while the numerical predictions were compared with experimental data, in terms of soil and tunnel horizontal acceleration, soil shear strains and tunnel deformations. The validated numerical models were then employed to further investigate several aspects of the system seismic response. Results indicate a rocking deformation mode coupled with the well-known racking distortion of box-type tunnels under seismic shaking. The effect of the soil-tunnel interface characteristics and soil yielding on the racking deformation of the tunnel, the dynamic earth pressures and shear stresses around the tunnel, as well as on dynamic lining forces is also reported. Soil yielding leads to post-shaking, residual, dynamic earth pressures, shear stresses and lining forces, especially in the case of flexible tunnels, while interface characteristics affect the distributions of these response parameters around the perimeter of the tunnel section. The ability of simplified seismic design methods for tunnels to predict the response is finally discussed, by comparing their predictions with the recorded data and the numerical results.



## 1. Introduction

Post-earthquake observations have demonstrated that tunnels and large underground structures may undergo extensive deformations or even collapse under strong earthquake loading, when seismic design provisions are not encountered (e.g. Sharma and Judd, 1991; Power et al., 1998; Wang, 1993; Iida et al., 1996).

Underground structures exhibit a quite distinct seismic response compared to the above ground structures, as the kinematic loading imposed on the structure by the surrounding ground prevails over inertial loads, stemming from the oscillation of the structure itself (Hashash et al., 2001).

Seismic response of underground structures and tunnels has been a subject of intense research by a series of experimental (Chou et al., 2010; Shibayama et al., 2010; Cilingir and Madabhushi, 2011a, 2011b, 2011c; Chian and Madabhushi, 2012; Lanzano et al., 2012; Chen et al., 2013; Tsinidis et al., 2015b; Abuhajar et al., 2015; Ulgen et al., 2015), numerical (Hashash et al., 2005; Anastasopoulos et al., 2007, 2008; Amorosi and Boldini, 2009; Kontoe et al., 2011, 2014; Debiasi et al., 2013; Baziar et al., 2014; Lanzano et al., 2015) and analytical (Huo et al., 2006; Bobet et al., 2008; Bobet, 2010) studies. However, several issues of the seismic response of box-type tunnels, including seismic earth pressures imposed on the tunnels side-walls, seismic shear stresses around the structure, and complex deformation modes of tunnels mobilized during shaking, are still under investigation. Along these lines, design provisions, specified in current guidelines for tunnels, are based primarily on simplified methods (e.g. Wang, 1993; Penzien, 2000; Hashash et al., 2001; ISO, 2005; Anderson et al., 2008; FHWA, 2009), the implementation of which, may lead to substantial differences in the seismic design (Pitilakis and Tsinidis, 2014).

In this paper, the above issues are explored by means of dynamic centrifuge testing and numerical analysis. The scope of this paper is threefold; (a) to provide experimental evidence on the seismic response of box-type tunnels in soft soil under earthquake motions and sine wavelets, (b) to evaluate the efficiency of numerical models that are often employed in tunnelling

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http://dx.doi.org/10.1016/j.tust.2016.07.008
0886-7798/

design practice, and (c) to compare the recorded and the computed response with the predictions of available simplified design methods. In this context, a series of dynamic centrifuge tests on scaled box-type model tunnels embedded in dry sand are initially presented. The tests were performed at the geotechnical centrifuge facility of the French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR) in Nantes, France, within the DRESBUS II TA action funded by the SERIES research project (Tsinidis, 2015; Tsinidis et al., 2015a). Following a detailed description of the experimental set up, salient parameters controlling the dynamic response of the soil-tunnel system, such as soil-tunnel relative flexibility, soil-tunnel interface characteristics and characteristics of the input motion, are discussed as part of the experimental program. In a second stage of the study, representative test cases are numerically analyzed by means of full dynamic analysis, accounting for the non-linear behavior of the soil and the soil-tunnel interface. The numerical results are compared with the recorded data to investigate the response mechanism mobilized between soil and tunnel under seismic loading and validate the numerical models. The ability of simplified seismic design methods for tunnels to predict the response is finally discussed, by comparing their predictions with recorded data and results from numerical analyses.

## 2. Dynamic centrifuge testing

### 2.1. Centrifuge facility

The experimental program was carried out at the geotechnical centrifuge of IFSTTAR (Chazelas et al., 2008) under a centrifugal acceleration of 40*g* (i.e. scale factor, N = 40). Earthquake input motions were applied at the base of the model through a specially designed actuator (Actidyn QS 80), which is capable of imposing both sinusoidal and real earthquake excitations up to 400 kg of payload mass (Chazelas et al., 2008). A large Equivalent Shear Beam (ESB) container was employed to mount the models, having inner dimensions 800 mm in length, 340 mm in width and 409 mm in depth. The box is designed to follow the shear deformations of the soil model, thus minimizing spurious boundary effects due to soil-container interactions (Escoffier, 2008).

**Table 1**
Fontainebleau NE 34 sand physical properties.

| | $\rho_s$ (g/cm$^3$) | $e_{max}$ | $e_{min}$ | $d_{50}$ (mm) | $\varphi_{crit}$ (°) |
|---|---|---|---|---|---|
| Fontainebleau NE 34 sand | 2.64 | 0.860 | 0.550 | 0.200 | 33 |

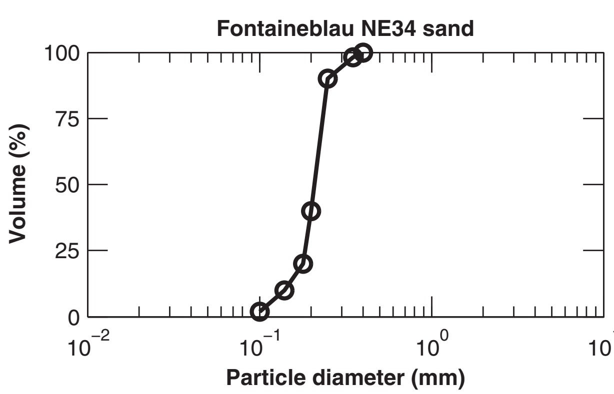


**Fig. 1.** Particle size distribution of Fontainebleau sand (Delfosse-Ribay et al., 2004).

### 2.2. Soil and model tunnels

The soil models were made of Fontainebleau NE 34 sand with a 'nominal' relative density at 70%. The physical properties of the specific sand fraction are presented in Table 1, whereas the particle size distribution is portrayed in Fig. 1.

Model-tunnels were manufactured by 2017 A aluminum alloy, implementing an electro-erosion technique to avoid pre-stresses (Fig. 2a). The mechanical properties of the specific aluminum alloy are given in Table 2. The dimensions of the tunnels (Fig. 2b) were deliberately chosen to model the desirable soil-to-tunnel relative flexibility (i.e. flexibility ratio, *F* in the range of 0.3–0.45 and 7–9 for the rigid and the flexible tunnel, respectively). Similarly, the external facades of the model tunnels were properly shaped, to model either rough or smooth interface characteristics. More specifically, rough soil-tunnel interface was formed by small grooves on the external facade of the models. The dimensions of these grooves were based on the sand granulometry and the dimensions of the tunnel sections. In particular, the grooves dimensions *R* and *AR* (Fig. 2c) were set equal to 100 µm and 200 µm, respectively. The internal dimensions of the models were kept constant, allowing the use of identical extensometers for all the test cases, as will be described in the ensuing. Based on the adopted centrifuge scaling factor (*N* = 40), the flexible model tunnels correspond to 1.88 × 2 (m) sections with an equivalent concrete wall thickness at 8 cm and a slab thickness at 32 cm, in prototype scale (assuming a modulus of elasticity E = 30 GPa for the equivalent concrete section). Accordingly, the rigid model tunnels correspond to 2.16 × 2 (m) sections of 27 cm wall thickness and 30 cm slab thickness (for the equivalent concrete section).

### 2.3. Test models preparation and instrumentation

An automatic hopper system was employed to form the sand deposit within the ESB container in a piecewise manner. The above

**Table 2**
Model tunnels mechanical properties.

| | Unit weight, γ (kN/m$^3$) | Elastic modulus, E (GPa) | Poisson ratio, v | Yield strength, $f_y$ (MPa) |
|---|---|---|---|---|
| Tunnel models | 2.7 | 71.00 | 0.33 | 400.00 |

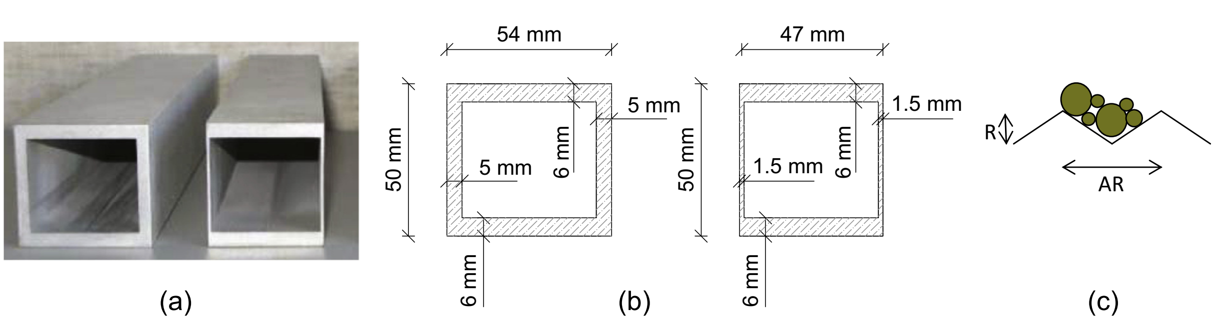


**Fig. 2.** (a) Model tunnel sections, (b) dimensions of the sections and (c) relation between the grain size of the sand and the dimensions of the grooves on the external facade of the model tunnels.