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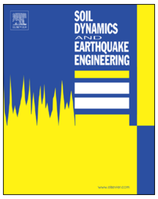

Vulnerability of floating tunnel shafts for increasing earthquake loading

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ABSTRACT

Fragility curves constitute the cornerstone in seismic risk evaluations and performance-based earthquake engineering. They describe the probability of a structure to experience a certain damage level for a given earthquake intensity measure, providing a relationship between seismic hazard and vulnerability. In this paper a numerical approach is applied to derive fragility curves for tunnel shafts built in clays, a component that is found in several critical infrastructure such as urban metro networks, airport facilities or water and waste water projects. The seismic response of a representative tunnel shaft is assessed using tridimensional finite difference non-linear analyses carried out with the program FLAC^{3D}, under increasing levels of seismic intensity. A hysteretic model is used to simulate the soil non-linear behavior during the seismic event. The effect of soil conditions and ground motion characteristics on the soil-structure system response is accounted for in the analyses. The damage is defined based on the exceedance of the concrete wall shaft capacity due to the developed seismic forces. The fragility curves are estimated in terms of peak ground acceleration at a rock or stiff soil outcrop, based on the evolution of damage with increasing earthquake intensity. The proposed fragility models allows the characterization of the seismic risk of a representative tunnel shaft typology and soil conditions considering the associated uncertainties, and partially fill the gap of data required in performing a risk analysis assessment of tunnels shafts.

1. Introduction

Strategic infrastructures such as metro lines, water supply or waste water systems, and underground airport facilities built in highly populated earthquake prone regions require a proper seismic risk assessment to foreseen potential failures and ensure earthquake preparedness. Although in most cases underground structures behave better than surface structures during earthquakes, significant damage has been reported in underground facilities subjected to strong ground shaking [1,2]. Especially for shallow underground structures built in medium to high plasticity soft soils, their susceptibility to damage can be increased, as the ground strains and velocities along with the accelerations, increase when approaching the ground surface [3]. Therefore, tunnel shafts may experience high bending moments as well as axial and transversal loads during earthquakes. Hence, it is important to estimate for different seismic scenarios the expected degree of damage for tunnel shafts, a component that is found in critical transportation and utility systems. Fragility functions, which quantify the probability of the structure to endure a certain degree of damage (e.g. minor, moderate, major) for a given ground motion intensity, is a required element in the vulnerability and risk assessment of tunnel shafts and associated infrastructures and networks. Moreover, modern tunnel shafts design is moving towards performance-based concepts to ensure both economy and safety and, thus, requires quantifying the global collapse risk of the network that belongs to.

Although traditionally fragility curves have been defined and established for buildings [4–7], recently the concept has been extended to lifelines and infrastructure components [8–10]. Fragility functions are essentially based on experts' opinions and field observations, or analyses and tests. Nevertheless, one limitation when dealing with geotechnical problems, such as floating tunnel shafts, is the lack of well documented field data regarding damage parameters (e.g. permanent displacements, cracking, and resisting force exceedance). This paper presents the application of the methodology proposed by Argyroudis and Pitilakis [11] and Argyroudis et al., [9], to develop numerically-derived fragility curves for tunnel shafts.

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2. Methodology

The general procedure for the derivation of analytical fragility curves is described in Fig. 1. The response of the soil-tunnel shaft coupled system is computed through a series of 3D fully nonlinear dynamic analyses for an increasing level of seismic intensity using the software FLAC^{3D}. The geometry, material properties, and structure details are parameters which describe the typology of the tunnel shaft and its capacity to withstand seismic loads. The seismic loads are function of the surrounding soil, seismic environment and the soil–shaft interaction. Representative soil profiles are selected based on commonly used classification schemes, such as the one by Eurocode 8 [12] so as to account for the effect of soil conditions on the response of the tunnel shaft. The selection of the seismic input motion is also essential in the seismic response analysis of the soil–shaft system. Different ground motion are selected in terms of amplitude, frequency content and duration. Damage is quantified in terms of the exceedance of the tunnel shaft concrete wall capacity, expressed in terms of the ratio of maximum tensional capacity of the shaft wall and the acting normal forces. In turn, damage is related to a rock or firm soil outcrop peak ground acceleration PGA_{rock}. Relating damage to PGA_{rock} directly rather than the actual peak ground acceleration in free field, PGA_{ff}, allows for a direct application in seismic vulnerability studies. Finally, fragility curves are derived for different damage states considering the primary sources of uncertainties. The fragility curves for shafts presented herein partially fill the gap of data required for performing a risk analysis assessment of floating tunnels shafts.

3. Numerical study

A parametric study was conducted in order to characterize the damage that a typical concrete floating tunnel shaft with a diameter, D, height, L_d, and wall thickness, t, of 14, 30, and 1 m respectively (Fig. 2), can exhibit for several seismic shaking scenarios varying from moderate to extreme ground shaking. Two idealized 50 m deep clay deposits were considered in this study, corresponding to ground type C and D, as defined in the Eurocode 8, EC8. The corresponding idealized soil profiles considered in each case are presented in Fig. 3. The water table was assumed to be at about 1 m below ground surface. Both normal and subduction type events were considered. Table 1 summarizes seismic events information used in the analyses. A total of six ground motions recorded during these events were selected, exhibiting different spectral acceleration amplitudes, frequency content, significant duration and seismotectonic environment. These ground motions were recorded either at rock or firm soil. Fig. 4 presents the response spectra of the selected motions together with the EC8 spectrum for soil class A, normalized with respect to their corresponding PGA. The time histories are scaled to five intensity levels of PGA (i.e. 0.15, 0.30, 0.45, 0.60 and 0.75 g) in order to calculate in the dynamic analyses the response of the tunnel shaft–soil system to an increasing seismic excitation. Thus, 30 cases were analyzed for each shear wave velocity profile. All the soil–shaft models were assumed with a bottom mat foundation 2 m thick, as usually considered in clays to avoid excessive uplift, which eventually could lead to bottom failure.

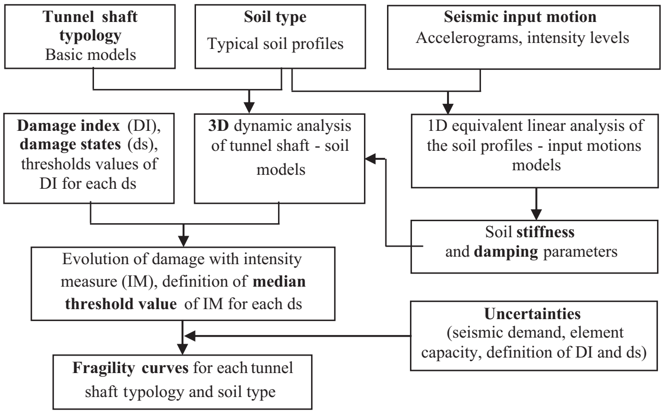

Fig. 1. Procedure for deriving numerical fragility curves for tunnel shafts.

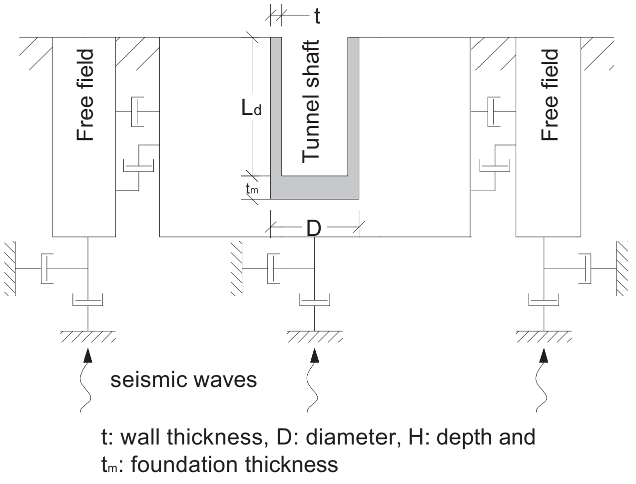

Fig. 2. Problem definition.

4. Dynamic soil properties

The empirical model proposed by Darendeli and Stokoe [13], was used to generate modulus degradation and damping curves, which take into account confining pressure effects, σ', plasticity index, PI, over consolidation ratio, OCR, the frequency of loading, f, and the number of loading cycles, N. To obtain these curves, the over consolidation ratio, OCR, was taken equal to one. Thus, they are only a function of plasticity index, PI. In this particular case, an average value of 90% and 150% was used for the generic profiles of ground type C and D respectively. Fig. 5 presents the corresponding curves used in the analyses, considering the variation of the confining stress for three depths.

5. Numerical model

The seismic analyses were carried out with a fully nonlinear finite difference hysteretic tridimensional model, using the program FLAC^{3D} [14], as depicted in Fig. 6. The shaft was simulated with linear elastic shell elements. This allows obtaining displacements, as well as shear forces, bending moments and axial forces acting at the tunnel shaft. The structural details of the tunnel shaft are given in Fig. 7, and the concrete properties are compiled in Table 2. The damping for the tunnel shaft wall was considered equal to 5%. Two lines of welded mesh were assumed in the design. The model depth is 50 m, which corresponds to the clay deposit thickness. The width and length of the model is four times the shaft diameter (i.e. 56 m), to avoid any undesirable reflection wave effects. Free field boundaries were used along the edges of the model. A rigid base was considered along the bottom of the model, to simulate the large dynamic impedance contrast existing at the site, in which a low shear wave velocity clay overlaid a high shear wave velocity