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# MILESTONE

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## 1.1 Introduction

Seismic risk assessment requires the definition of fragility curves which define the probability of exceedance of a predefined limit state. The complexity related to the characterization of the soil-foundation system along with the common credo in the beneficial effects associated with the interaction between the soil, foundation and structure led over the years to develop fragility functions considering fixed-base structures. The modification of the fragility functions of structures founded on soft soil with respect to the typical fixed-base assumption has been recognized by different authors (Sáez et al., 2011; Rajeev and Tesfamariam, 2012; Pitilakis et al., 2014; Karapetrou et al. 2015; de Silva, 2020; Petridis and Pitilakis, 2020; Cavalieri et al., 2020). These studies reveal that the shift of fragility functions from the fixed-base reference case is expected to be significant in deformable soil conditions, leading to either beneficial or unfavorable effects, depending on the dynamic properties of the soil, the foundation (Piro et al., 2020), the structure and the characteristics (frequency content, amplitude, significant duration) of the input motion (Dutta et al., 2004). Even though the results of such studies provided the scientific community with valuable knowledge at site-specific vulnerability assessment, the reliability at urban scale is assessed with certain limitations. Indeed, despite all the previous investigations and efforts not all the possible SFSI scenarios have been covered so far, making the existing fragility functions accounting for SFSI inadequate for large-scale analyses. To this aim we propose a new methodological framework for the development of generalized fragility functions applicable to different reinforced concrete and masonry buildings for a great variety of soil-foundation systems that can be encountered in urban environment.

## 1.2 Proposed framework for development of fragility curves including SFSI and site effects

We to propose and quantify an analytical methodology to assess the fragility functions for different building classes founded on shallow foundations taking into account SFSI and site-effects (Amendola and Pitilakis, 2022). Figure 1 summarizes the main steps of the methodological framework. All the analyses are conceived to be implemented in the open-source OpenSees software (Mazzoni et al., 2006). To formally consider the aleatoric uncertainties related to the so-called record-to-record variability, a large set of input ground motions recorded on rock/firm-soil is selected to perform all the dynamic cloud analyses (Jalayer et al. 2017). The modification of the selected records due to the local site effects is quantified by performing one dimensional (1D) numerical simulations of seismic site response performed on virtual stratigraphic profiles. The selected soil profiles are conceived considering different shear wave velocities $V_{S,30}$ (i.e. ranging from 150 to 450 m/s) thus pertaining to the soil types B, C and D according to EC8 (CEN, 2004).

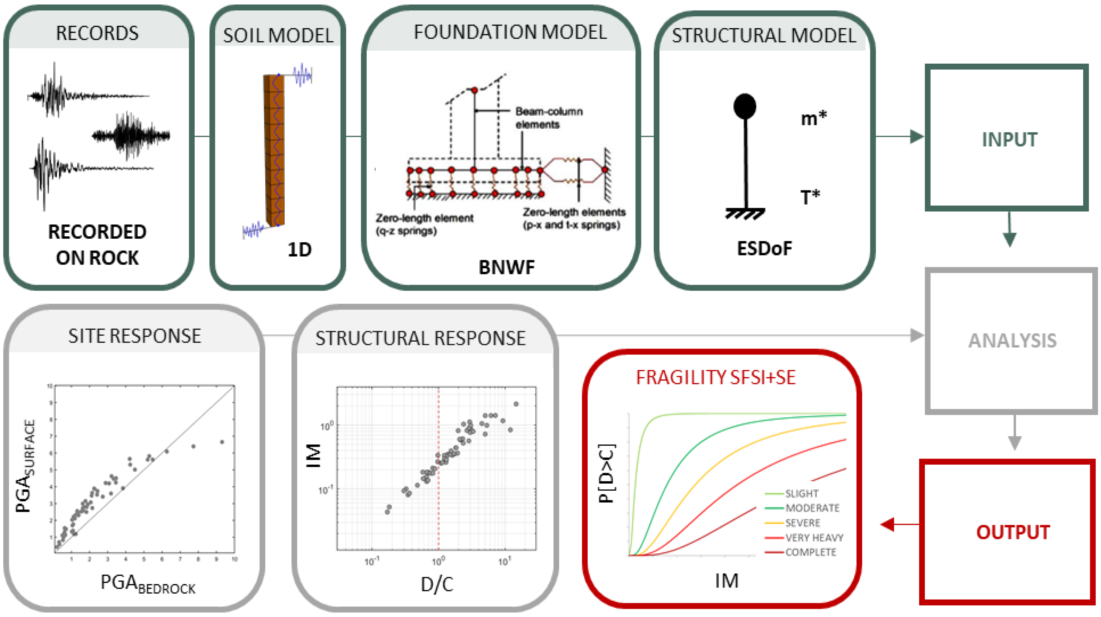

*Figure 1 Flow chart assessment of the proposed methodology for the fragility assessment of structures considering SFSI and site-effects at an urban scale.*

The so-modified input motions are then adopted to perform dynamic analyses following the equivalent single degree of freedom (ESDoF) systems approximation for the superstructure (D'ayala et al., 2014). Following this approach, the superstructure is modeled with a single degree of freedom system characterized by a non-linear hysteretic behavior. To reduce the computational effort (as implicitly demanded from seismic fragility assessment of building portfolios) it's convenient to classify buildings through a combination of a few attributes such as force resisting mechanism, height and code level. This classification, also known as taxonomy (e.g. GEM taxonomy, D'ayala et al., 2014), is justified considering that the structures with similar characteristics are more prone to experience similar behaviour when subjected to seismic forces. Different "average" structural types (from now on building classes) are selected representative of the exposure model assigning specified constitutive laws to each building class. At the same time, the compliance of the foundation subsoil is considered using the Beam-on-Nonlinear-Winkler-Foundation (BNWF) concept (NIST, 2012). The advantage of this model is the possibility to directly account for non-linear soil-foundation behavior which is expected to occur especially at higher intensity measures levels. For the BNWF modeling, to cover different scenarios of foundation systems that can be encountered in urban environment, the parameters mostly affecting the interaction problem (Veletsos and Meek, 1974), such as the slenderness ratio, $H/B$ (where $B$ is the characteristic foundation half-length), the soil to structure relative ratio, $\sigma$, and the structure to soil relative inertia, $\delta$, are parametrically investigated. The results of the dynamic analysis are processed to calculate the probability of exceedance of four different limit states (ranging from slight to complete damage state) given the intensity measure (*IM*). We selected two different intensity measures for the fragility computation. Pseudo-spectral acceleration at periods close to the fundamental period of the structure, $Sa(T)$, and average spectral acceleration, *AvgSa*. The latter is of particular interest in SFSI studies since it allows the comparison between fragility functions developed for different compliant systems and the reference curves considering the fixed-base assumption. Both intensity measures are computed for the set of input records (i.e. recorded on rock/very stiff soil) and from the free-field motions resulting from the site response analysis, referred in the following as $Sa(T)_R$, $AvgSa_R$ and $Sa(T)_{ff}$ and $AvgSa_{ff}$ respectively. Finally, the uncertainty of the fragility parameters is estimated through the standard deviation, $\beta_{tot}$ which is modelled by the combination of the different variability sources including the building-to-building variability, the uncertainty in the damage states and the record-to-record variability implicitly considered by the randomness of ground motions.

## 1.3 Output

The results of the proposed methodology are fragility functions developed for building classes belonging to different SFSI scenarios investigated by changing the dimensionless parameters most influencing the response of structures founded on soft soil profiles. The regression analyses were performed considering all the above-mentioned *IMs* (i.e. $Sa(T)_R$, $AvgSa_R$, $Sa(T)_{ff}$ and $AvgSa_{ff}$). Figure 2 reports the comparison of fragility functions developed for a mid-rise regularly infilled structure designed with low-code prescriptions (namely CR-LFINF-DUL-H4 following the GEM taxonomy (D'ayala et al., 2014)) by changing the *H/B ratio*, the $\delta$ ratio and the $V_{s,30}$ for all the predefined limit states. All in all (see for example Figure 2a), the result of the analyses for the flexible foundations, i.e. considering SFSI and site-effects (dashed lines) produce a shift to the left of the fragility curves compared to the fixed-base case (continuous lines), thus resulting into an increase of the structural fragility. As a matter of fact, the fragility shift is more pronounced for very soft soil profiles, see for example Figure 2a developed for the virtual soil profile corresponding to $V_{s,30}$ 180 m/s compared to Figure 2b for $V_{s,30}$ 360 m/s.

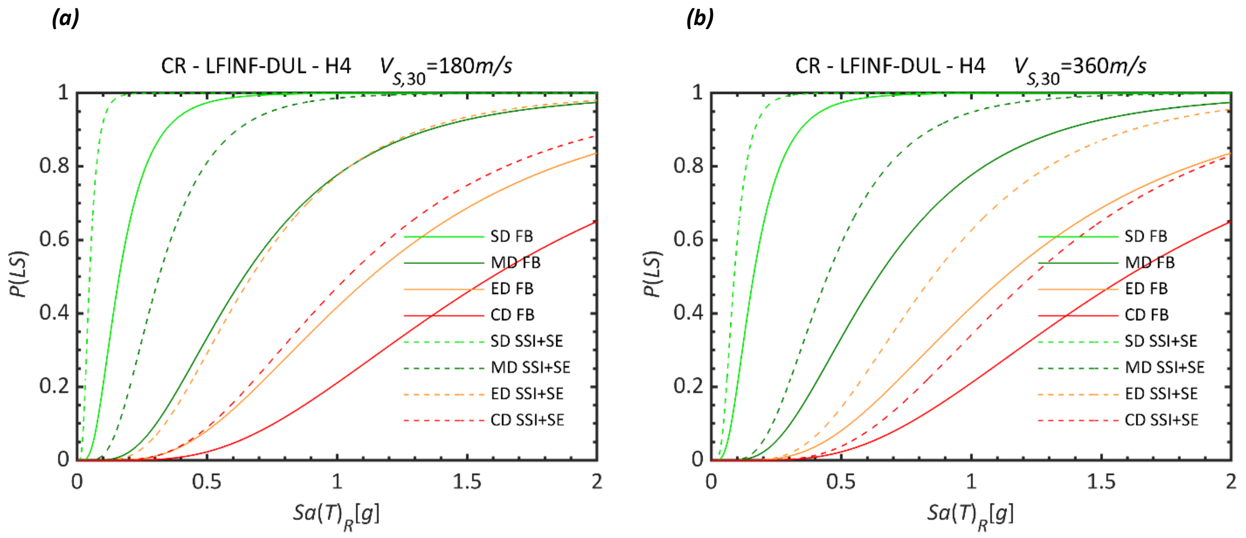

*Figure 2 Comparison between fragility functions in terms of $Sa(T)_R$ developed for one reference building class, i.e. CR-LFINF-DUL-H4 considering the structure fixed at its base (continuous lines) and SFSI and site-effects for one BNWF system characterized by H/B=1, δ=0.1 and (**a**) $V_{s,30}$=180m/s and (**b**) $V_{s,30}$=360m/s (dashed lines).*

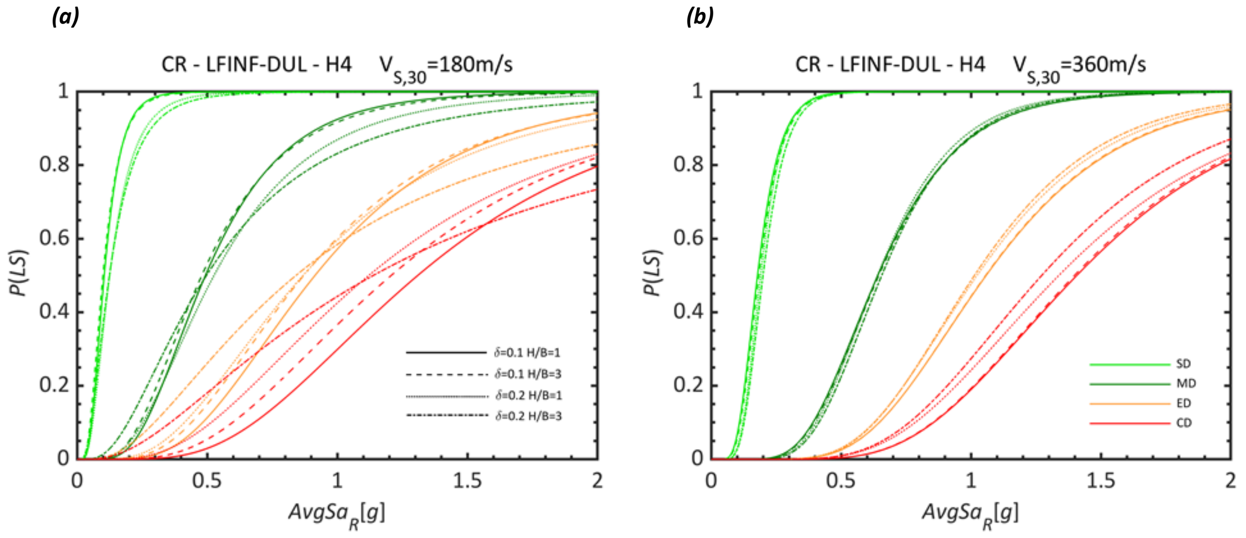

*Figure 3 Fragility functions in terms of $AvgSa_R$ developed for one reference building class, i.e. CR-LFINF-DUL-H4 considering SFSI and site-effects accounting for different hypotheses on the BNWF system, i.e. by H/B=1 and δ=0.1 (continuous lines), H/B=3 and δ=0.1 (dashed lines), H/B=1 and δ=0.2 (dotted lines) and H/B=3 and δ=0.2 (dashed-dot lines) for **(a)** very soft soil profile characterized by $V_{s,30}$=180m/s and **(b)** soft profile characterized by $V_{s,30}$=360m/s.*

When comparing the fragility functions developed for the selected building class resting on the same soft soil profile but by accounting for different hypotheses on the BNWF systems, i.e. by varying the slenderness and structure-soil relative inertia ratio it is possible to appreciate the variability associated with SFSI phenomenon in the fragility computation (see Figure 3). This variability is likely to be more pronounced for high damage states due to the non-linear soil-foundation phenomenon occurring for high *IM* values.

## 1.4 Applicability

One of the greatest uncertainties to study the problem of soil-structure-interaction is the definition of the main features defining the foundation system. With this in mind, the applicability of the proposed approach is based on globally available data regarding the soil parameters, the foundation, and the building taxonomy thus making it easily applicable for risk assessment at different cities. In particular, the soil parameters can be defined on the base of $V_{s,30}$ maps derived, just to mention few, from proxies such as the slope (Allen and Wald, 2007) or the local geology (Forte et al., 2019). The main features characterizing the foundation, in lack of local data, can be retrieved from the building print area as available in the OpenStreetMap ([http://www.openstreetmap.org/](http://www.openstreetmap.org/)). Lastly, the parameters taken to define the specific hysteretic low adopted are defined based on the non-linear backbone curve (capacity curve) available in the literature for different building classes in the GitHub repository https://github.com/lmartins88/global_fragility_vulnerability (Martin and Silva, 2020).

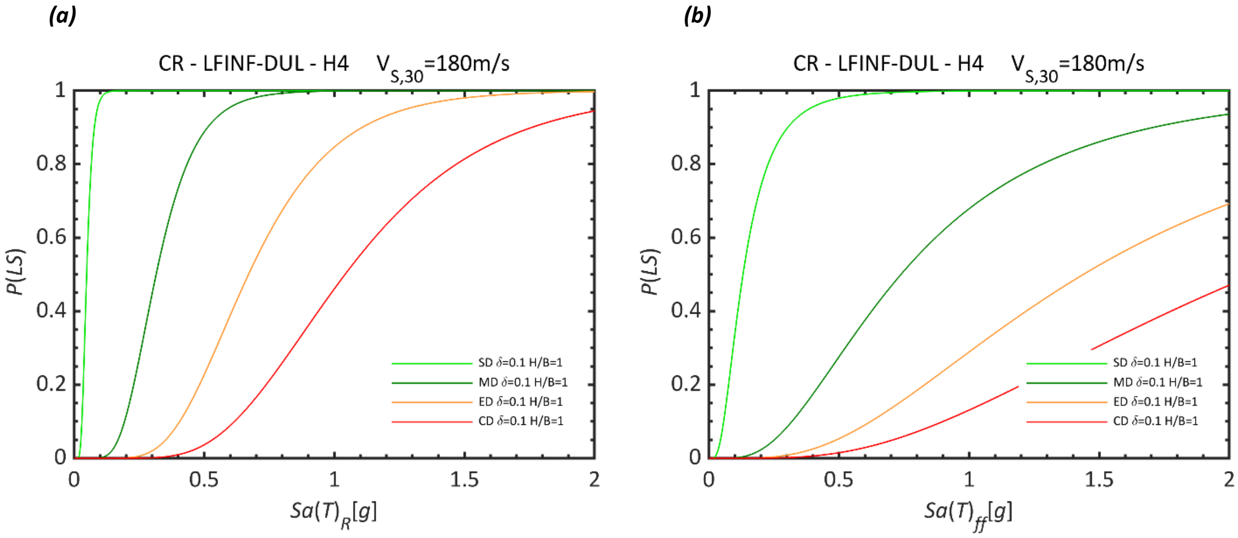

*Figure 4 Fragility functions developed for one reference building class, i.e. CR-LFINF-DUL-H4 considering SFSI and site-effects for one BNWF system characterized by* $V_{s,30}$*=180m/s, H/B=1, δ=0.1 in terms of (**a**) Sa(T)*$_R$ *and (**b**) Sa(T)*$_{ff}$.

Seismic fragilities including site-effects and SFSI where the given intensity measure refers to the analysis input records (i.e. as recorded on rock/stiff soil, Figure 4a) can be used when the hazard scenario is referring to the underlying bedrock or generally adopted to gain insights into the differences with respect to the common assessment practice which considers fixed-base structures and neglects the modification of the input motion due to the deformability of the soil profile (as in the case of Figure 2). On the other hand, the fragility curves as function of intensity measures defined from the free-field motions (Figure 4b), can be also used in the framework of a risk assessment where the hazard includes site effects adopting either code- or research-based amplification factors or moreover where the hazard scenario comes directly from physics-based numerical simulations (Paolucci et al., 2014).

## 1.5 Ongoing development

The methodological framework will be updated considering embedded and deep foundations, also considering a larger range of input motions recorded on rock (synthetics or from physic-based simulations).

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