Nonlinear Subsoil Seismic Response in Boumerdes: Toward Seismic Microzonation and Urban Planning Support

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ABSTRACT

The accurate estimation of earthquake-induced ground motion at a specific site is crucial for evaluating seismic hazards, including soil deformation, ground failure, and potential structural damage. This study investigates the seismic response of subsurface soil profiles in the Boumerdes region (Algeria) using numerical site response analysis. The assessment focuses on Peak Ground Acceleration (PGA) and response spectra while accounting for soil nonlinearity through both equivalent-linear and fully nonlinear approaches. The input motion corresponds to the ground excitation recorded during the Boumerdes earthquake of May 21, 2003. The results reveal significant variations in surface ground motion, characterized by amplification or attenuation relative to the bedrock input motion, highlighting the strong influence of local site effects. These findings contribute to a better understanding of seismic wave propagation in local soil conditions and provide a scientific basis for site-specific seismic microzonation of Boumerdes, supporting improved seismic risk mitigation and resilient urban planning in this seismically active region. These findings are also relevant to urbanized areas, where land-use choices require site-specific seismic information.

Keywords-seismic site response; soil plasticity; amplification; seismic microzonation

I. INTRODUCTION

In a rapidly urbanizing city such as Boumerdes, understanding local site effects is essential for reducing seismic exposure and informing safer land development. Most of the damage caused by earthquakes results from ground shaking of the Earth's crust. Such damage may be the direct consequence of ground vibrations originating from the seismic source; however, ground movements, such as landslides or soil instability, may also occur simultaneously, leading to additional types of structural and material damage. One of the most significant damage-related factors is the duration of ground shaking, which largely depends on the local soil conditions. Depending on the subsurface geological configuration and soil characteristics, seismic waves may be either amplified or attenuated, resulting in corresponding variations in the level of damage. These phenomena are commonly referred to as site effects. The importance of soil behavior under dynamic loading conditions has been highlighted. For instance, the dynamic response of saturated clayey soils under impact loading has been experimentally investigated, emphasizing the significant influence of soil properties on wave propagation and energy dissipation [1-2]. Similarly, soil–structure interaction has been analyzed using the scaled boundary Finite Element (FE) method, demonstrating how local soil conditions can affect stress distribution and structural response during dynamic events [3]. These contributions underline the necessity of incorporating both soil dynamics and soil–structure interaction in seismic site effect assessments.

Given their significance, some of these effects are partially incorporated into seismic design codes through response spectra. Nevertheless, a more accurate consideration of site effects in seismic regulations and urban planning remains highly desirable [4-5]. Achieving this objective requires both a thorough understanding of the underlying physical mechanisms and the development of reliable methods for their quantification. The behavior of soils under cyclic loading is often nonlinear and depends on several factors [6], including loading amplitude, number of cycles, soil type, and in-situ confining pressure. Even at relatively small strain levels, soils exhibit nonlinear behavior. Therefore, soil nonlinearity must be incorporated into any site response analysis. One-dimensional site response analysis methods are widely used in both research and engineering practice to evaluate the influence of soil deposits on seismic wave propagation [4-6]. These methods can generally be classified into two main categories: (1) frequency-domain analyses based on the equivalent-linear approach, such as the widely used SHAKE91 program, and (2) time-domain analyses based on fully nonlinear models.

The objective of this study is to compare equivalent-linear and nonlinear seismic responses of soil profiles in the Boumerdes region, which was selected due to its high seismic hazard and documented vulnerability, particularly following the 2003 earthquake, as well as the significant variability of its local geotechnical conditions, in order to better characterize the actual behavior of local soils and to support the development of a site-specific seismic microzonation for this region. The obtained results are consistent with the literature, showing reduced amplification and frequency shifts under nonlinear behavior, confirming the adopted approach. Beyond structural design, this comparison can also support urban seismic microzonation and help guide the siting of strategic facilities in exposed districts [7-8].

II. METHODS FOR SEISMIC RESPONSE ANALYSIS OF SOIL PROFILES

A. *Equivalent-Linear Site Response Analysis in the Frequency Domain (SHAKE2000)*

The SHAKE code assumes an equivalent linear viscoelastic soil behavior. In the equivalent-linear model, the shear modulus G and the damping ratio D are assumed to depend on the amplitude of shear strain. The equivalent-linear analysis is performed iteratively, updating the values of G and D until they become compatible with the effective shear strain induced in each layer of the numerical soil profile [9-10]. The shear modulus reduction curve (G/G0) and the variation of the damping ratio D with the shear strain level (γ) were defined based on typical relationships reported in the literature as a function of the Plasticity Index (PI). The results of the equivalent-linear analysis are shown in Figure 1.

B. *Nonlinear Site Response Analysis in the Time Domain (Plaxis v8.2)*

Nonlinear two-dimensional dynamic response analyses are performed by formulating the equations of motion of an FE model in an incremental form and then integrating them over time [11-12].

For the case of base-induced loading, the global equation of motion can be expressed as:

$$[\mathrm{M}]\{\ddot{\mathrm{u}}\} + [\mathrm{C}]\{\dot{\mathrm{u}}\} + [\mathrm{K}]\{\mathrm{u}\} = -[\mathrm{M}][\mathrm{I}]\ddot{\mathrm{u}}_{\mathrm{g}}(\mathrm{t}) \qquad (1)$$

where [M] is the mass matrix, [C] is the viscous damping matrix, [K] is the stiffness matrix, $\{\ddot{u}\}$ is the nodal relative acceleration vector, $\{\dot{u}\}$ is the nodal relative velocity vector, $\{u\}$ is the nodal relative displacement vector, $\ddot{u}_g$ is the base acceleration of the soil column, and [I] is the unit vector. The soil response is obtained from a constitutive model that describes the cyclic behavior of the soil. The dynamic equilibrium equation (1) is solved numerically at each time step using a time integration method, for example, the Newmark method (1959). Prior to performing the nonlinear time-domain analysis, the viscous damping and stiffness parameters must first be calibrated.

B.1. Calibration of Stiffness and Viscous Damping Parameters for Finite Element Analysis

The simulation of wave propagation through FE analyses, employing a depth-dependent linear viscoelastic model, requires careful definition of the elastic and viscous parameters for each soil sublayer. Indeed, the results are highly sensitive to the assumed stiffness and damping profiles with depth (Figures 2(a) and 2(b)).

A recently developed procedure for calibrating viscoelastic parameters has been proposed and adopted for use in FE dynamic analyses [13]. In each FE analysis, shear modulus (G) and damping ratio (D or ξ) profiles were defined to reproduce the corresponding SHAKE2000 analysis results. To this end, the numerical models in PLAXIS [13-14] were subdivided into the same number of layers as used in SHAKE2000, and for each layer, appropriate values of G and D were assigned based on the shear strain levels obtained from the SHAKE2000 analysis [9], corresponding to the depth of the layer.

Figures 2(a) and 2(b) depict the G and D profiles adopted in the FE analysis for the Foes site subjected to Keddara St1 E–W seismic excitation.

The Rayleigh damping used in the simulations is defined by selecting the coefficients α_R and β_R (Figure 3), which depend on the damping ratio D and the adopted frequency range f_m - f_n. Several calibration procedures have been proposed in the literature to identify the f_m - f_n interval. In particular, it is proposed to choose fm as the first natural frequency of the soil deposit f1, while fn is assumed to be n times fm, where n is the largest odd integer less than or equal to the ratio f_p/f_1 (with f_p being the predominant frequency of the seismic motion and f_1 the fundamental frequency of the soil deposit) [14].

In the dynamic analysis, the base of the mesh was assumed to be rigid, while the lateral boundaries were modeled using the viscous boundaries proposed by [15].

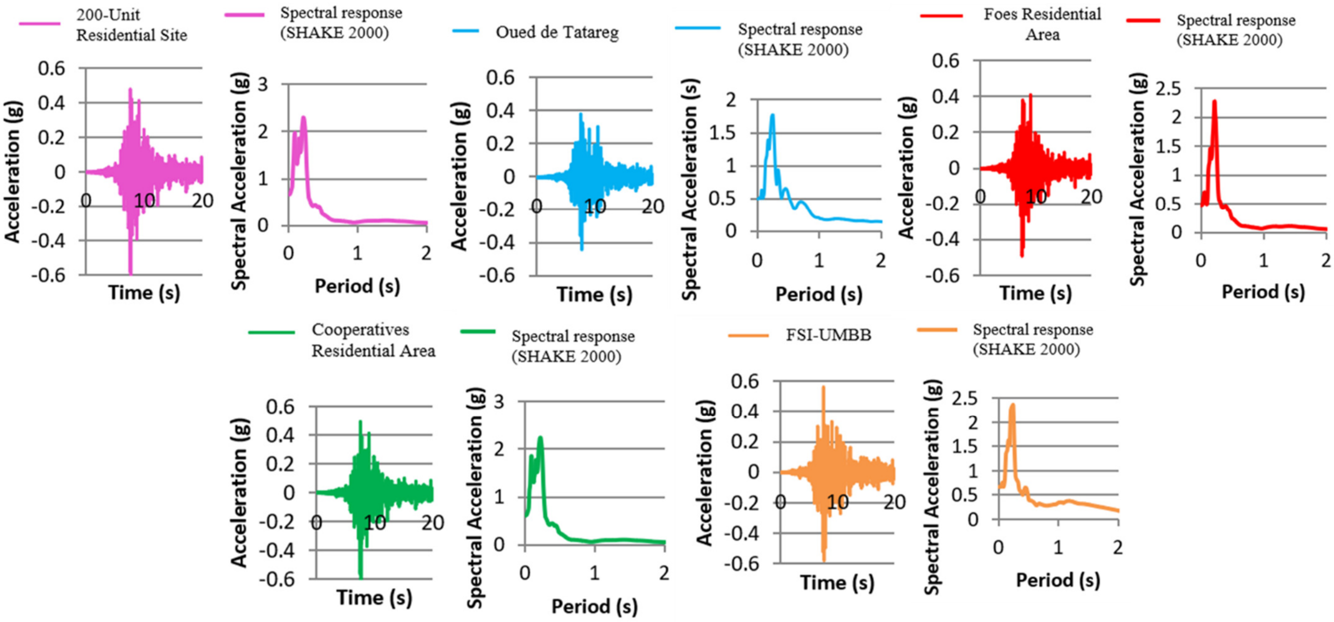

Fig. 1. Equivalent-linear analysis results showing acceleration, amplification, and response spectra.

The characteristic element size in the central part of the domain in the PLAXIS analyses was always chosen to satisfy the condition that the FE node spacing, Δl_{node}, should be approximately 1/10 to 1/8 of the wavelength, corresponding to the maximum frequency component (f_{max}) of the input motion (seismic signal):

$$\Delta l_{node} \leq \frac{\lambda_{min}}{8-10} = \frac{V_{s,min}}{(8-10)f_{max}} \qquad (2)$$

where $V_{S,min}$ denotes the minimum shear wave velocity. The corresponding mesh dimensions employed in the analyses are summarized in Table I.

TABLE I. MESH DIMENSIONS USED IN THE FE ANALYSES

fmax (Hz)	Vs (m/s)	ΔL=Vs /(10-8)fmax
25	274.68	1.09872

In the current profile analyses, a "fine" mesh was employed with a mesh element size of 1.58 m.

B.2. Calibration of Model Dimensions in the FE Analyses

The numerical investigation of this issue was carried out using PLAXIS, employing the viscous boundaries proposed in [15, 16] and using soil profile models with varying element sizes. The viscoelastic analyses described in this section were simulated assuming the standard parameters (C1=1.0 and C2=0.25) [15]. The horizontal mesh size, L, was set equal to 3, 4, 5, 6, 7, and 8 times the thickness h of the soil profile. In this context, the results obtained from SHAKE2000 were used as a reference. As an example, Figure 4 provides the comparison of surface free-field acceleration responses obtained for different soil profile dimensions at the Oued de Tatareg site, subjected to the Boumerdes earthquake (Keddara station, E–W component).

The similarity between the PLAXIS analysis results for L = 8 h and the reference SHAKE2000 analysis is evident. A satisfactory agreement between the response spectra from the equivalent-linear analysis (SHAKE2000) and the time-domain FE analysis (PLAXIS) is achieved for L = 4 h. This value can be considered a good compromise between accuracy and the computational time required for the time-domain analysis. The same trend was observed in all other cases studied. Furthermore, no significant differences were identified in the numerical results when varying the parameters a and b [15] within the range [0, 1]. The dimensions of the adopted numerical model are summarized in Table II.

TABLE II. DIMENSIONS OF THE ADOPTED NUMERICAL MODELS

Site	FE model dimensions
200-unit residential site	8 h
Oued de Tatareg	4 h
Foes residential area	5 h
Cooperatives residential area	8 h
FSI-UMBB	8 h

B.3. Nonlinear Site Response Analysis with a Mohr–Coulomb Model

In order to study the effects of nonlinearity on seismic wave propagation, plasticity was introduced into the FE viscoelastic analyses via a non-associated visco-elasto-plastic model, based on the Mohr–Coulomb criterion with a zero dilatancy angle.

III. SEISMIC ACTIVITY IN THE BOUMERDES REGION

The earthquake was felt up to 250 km from the epicenter, where the recorded acceleration reached 0.02 g. The main shock was recorded by several stations of the national accelerograph network operated by the CGS. A total of 13 stations were used to characterize the seismic motion, with the closest located 20 km from the epicenter as determined by the national accelerograph network, and the farthest at 150 km [17].

The municipality of Boumerdes was heavily affected by the earthquake of May 21, 2003 [18-19], which occurred in the region. In this work, the two-dimensional seismic response at five sites within the municipality is studied. Figure 5 illustrates the Foes site, which experienced significant damage; the 11 December 1960 Cooperatives site, which also suffered substantial damage; the Oued de Tatareg site; the FSI-UMBB site (University of Boumerdes); and the 200 Housing Units site in Boumerdes.

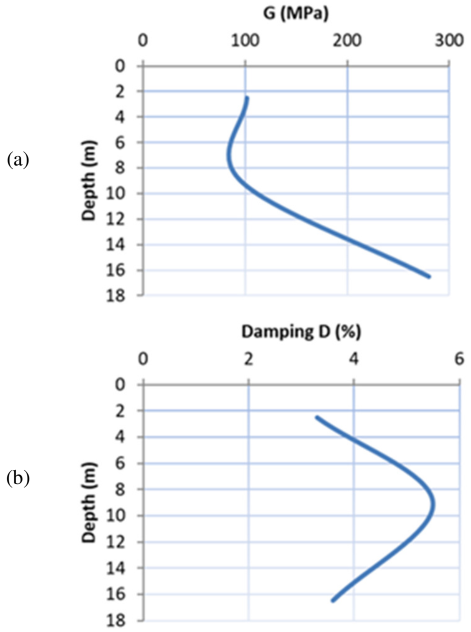

Fig. 2. (a) Shear modulus and (b) damping ratio (D) profiles assumed in the FE viscoelastic analyses, derived from SHAKE2000 results (Foes site subjected to Keddara St1 E–W seismic input).

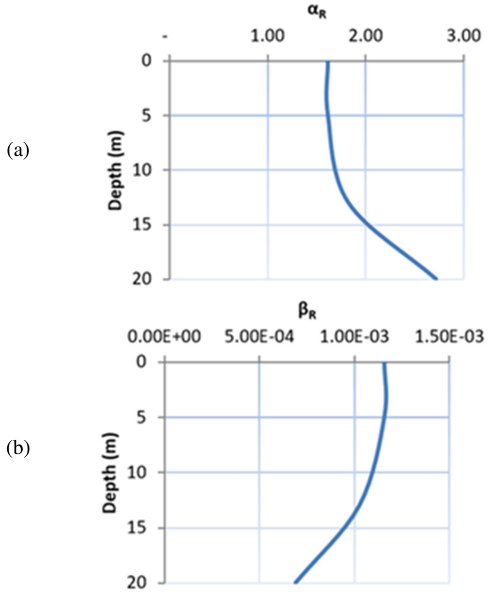

Fig. 3. Assumed Rayleigh damping coefficients (α_R and β_R) in the FE viscoelastic analyses of the Foes city soil profile subjected to Keddara St1 E–W seismic input motion.

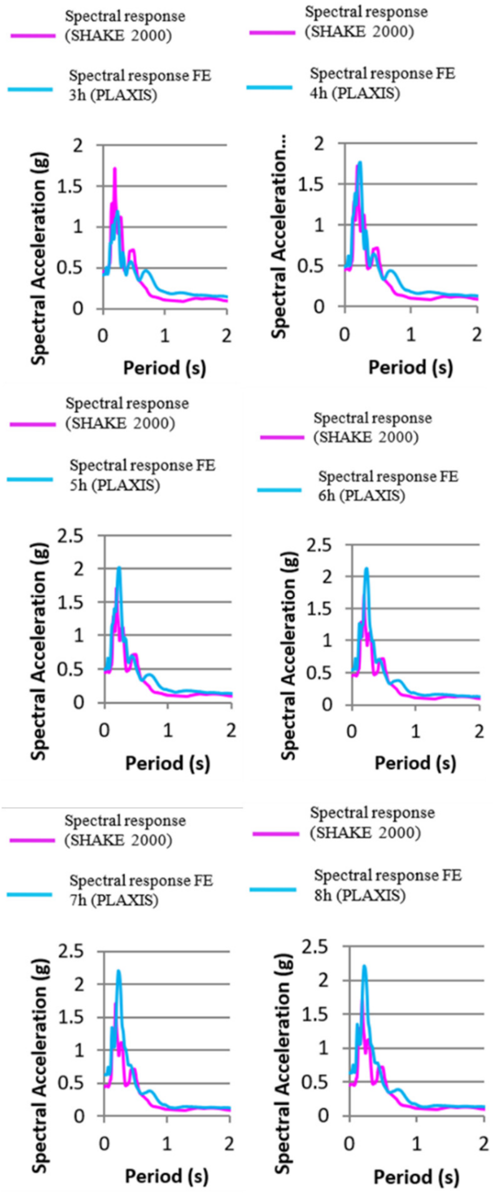

Fig. 4. Comparison of surface acceleration response spectra from SHAKE2000 and PLAXIS viscoelastic analyses for various soil profile dimensions at the Oued de Tatareg site, subjected to the Keddara St1 E–W seismic input.

IV. RESULTS OF THE NONLINEAR ANALYSIS

The results of the nonlinear time-domain analysis based on a Mohr–Coulomb model are presented in Figure 6. The obtained results indicate that the reliability of the seismic analysis primarily depends on the quality and representativeness of the data used to characterize the geotechnical profile of the site. Indeed, even when different soil models or computational tools are employed, the accuracy of the calculated accelerations, amplification functions, and response spectra remains directly related to the reliability of the input parameters, particularly those associated with FE analyses, such as the model dimensions and the Rayleigh damping coefficients α_R and β_R.

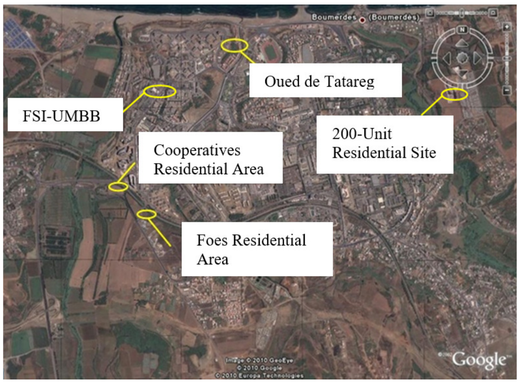

Fig. 5. Map showing the locations of the investigated sites.

V. CONCLUSION

Regardless of the soil model adopted or the computational tool used, the accuracy and reliability of the calculated quantities are primarily dependent on the credibility of the input data used to define the soil profile. In this context, the Boumerdes region was selected due to its high seismic hazard and vulnerability, notably highlighted by the 2003 earthquake, as well as the variability of its geotechnical conditions. The results of the seismic site study are used for the design and dimensioning of structures to be built. These results can be presented in various forms, such as amplification functions, free-field surface accelerations, or response spectra.

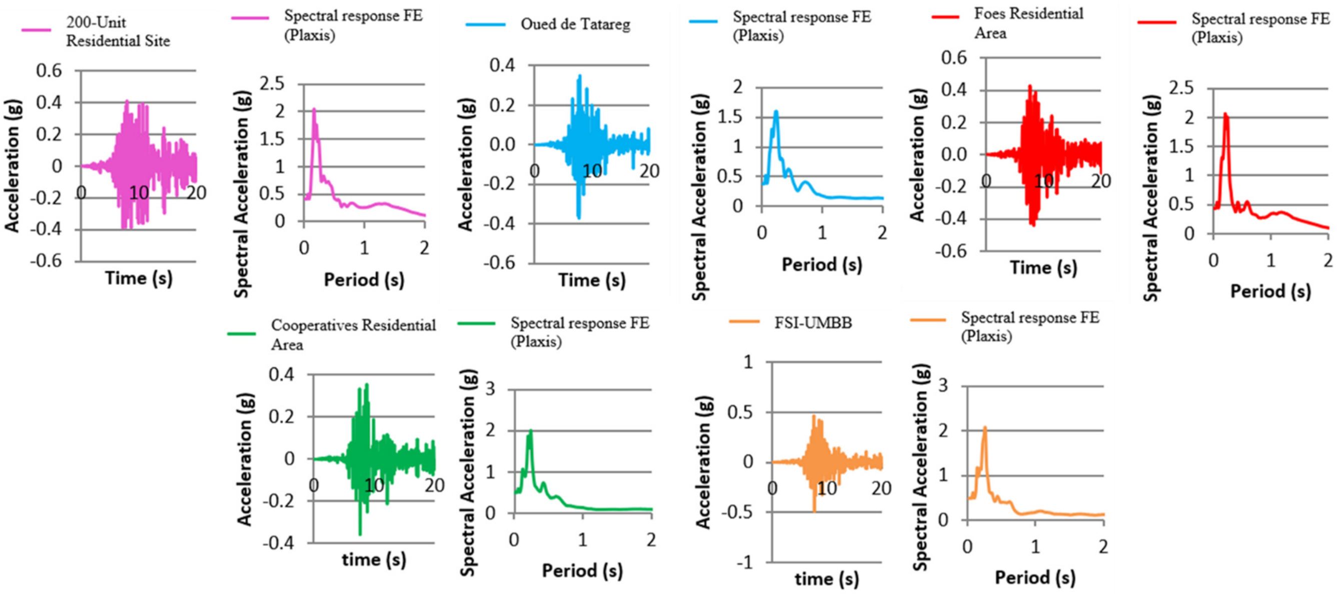

Fig. 6. Nonlinear analysis results showing acceleration and response spectra.

The use of a response spectrum derived from an equivalent-linear study may sometimes be insufficient and can lead to an overestimation of the seismic site response, thereby highlighting the need for detailed nonlinear analyses and the derivation of site-specific design spectra. These findings are consistent with studies conducted in other seismic regions, where a reduction in amplification and a shift in frequencies are generally observed at high strain levels, although local site conditions may induce specific variations in seismic response. The main contribution of this work lies in the development of an integrated comparative framework combining equivalent-linear and fully nonlinear Finite Element (FE) approaches, calibrated using site-specific geotechnical data and real earthquake records from the 2003 Boumerdes event. This dual approach enables a more reliable characterization of soil behavior under seismic loading and provides a robust basis for deriving site-specific seismic design spectra. Furthermore, the study introduces a practical methodology for coupling numerical site response analysis with urban-scale seismic microzonation, thereby bridging the gap between advanced geotechnical modeling and decision-making tools for urban planning. By explicitly linking local amplification effects to land-use strategies, this work contributes to the development of risk-informed planning frameworks. At the urban scale, these findings should be incorporated into planning documents and zoning regulations to ensure that local amplification effects are considered in land-use decisions and in the siting of strategic facilities. In parallel, GIS/Web-GIS decision-support tools can facilitate the translation of microzonation results into operational maps for prioritizing seismic risk-reduction actions. Moreover, these findings contribute to the development of risk-informed urban planning strategies, where construction regulations, zoning decisions, and land-use planning can be adapted according to site-specific seismic behavior. This approach enhances urban resilience and supports sustainable development in earthquake-prone regions.

DECLARATION OF COMPETING INTERESTS

Not applicable to this work.

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DATA AVAILABILITY

The seismic input data used in this study are based on the accelerometric records of the May 21, 2003, Boumerdes earthquake provided by the Algerian Center for Research in Astronomy, Astrophysics, and Geophysics (CRAAG/CGS) and reported in [17-20]. The geotechnical data used to characterize the investigated soil profiles were obtained from the National Laboratory for Housing and Construction (LNHC), Algeria. Additional numerical and seismic response data used for the calibration and validation of the equivalent-linear and nonlinear analyses were derived from published numerical and experimental studies available in [9, 10]. The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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