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Original paper

Simulated of earthquake wave compatible with design spectrum

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Abstract: Relevance. Artificial accelerograms are essential for seismic design, particularly in regions with limited strong motion data. In Armenia, the scarcity of such records hinders accurate seismic hazard assessments and structural design. **Aim.** This study aims to develop a new methodology for generating artificial accelerograms based on spectral normative curves, addressing the lack of strong earthquake data in the Republic of Armenia. **Methods.** The approach incorporates the only strong-motion record from the 07.12.1988 Spitak earthquake, supplemented with weaker local earthquake data ($M_w \geq 3.5$). By accumulating and processing these records, synthetic accelerograms are constructed to reflect realistic amplitude and frequency characteristics for various soil conditions. A dedicated software tool was developed to generate accelerograms consistent with spectral curves. **Results.** The proposed methodology enables the extrapolation of strong-motion accelerograms across different Armenian regions, contributing to the development of seismic hazard maps, including ground acceleration distributions and response spectra. The approach improves the accuracy of predicted ground motions compared to traditional dynamic curves lacking empirical support. The generated accelerograms can be applied in structural analysis, hazard assessment, and refinement of seismic design regulations. While developed for the Armenian Seismic Code, the methodology can be adapted to other international standards, broadening its relevance in global earthquake engineering.

Keywords: artificial accelerograms, seismic hazard assessment, response spectra, soil amplification, Spitak earthquake, seismic design regulations, spectrum-compatible ground motions.

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Оригинальная статья

Моделирование сейсмических воздействий в соответствии с нормативными спектрами реакции

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Резюме: Актуальность работы. Синтетические акселерограммы крайне важны для сейсмостойкого проектирования, особенно в регионах с ограниченным количеством записей сильных движений. В Армении недостаток таких данных затрудняет точную оценку сейсмической опасности и конструктивный расчет сооружений. **Цель исследования.** Данное исследование направлено на разработку новой методики генерации синтетических акселерограмм на основе нормативных спектральных кривых, что позволит компенсировать нехватку данных о сильных землетрясениях в Республике Армения. **Методы.** В основу методики положена единственная запись сильного движения от Спитакского землетрясения 07.12.1988, дополненная данными о более слабых местных землетрясениях ($M_w \geq 3.5$). Путем накопления и обработки этих записей синтезируются акселерограммы, достоверно отражающие амплитудно-частотные характеристики для различных грунтовых условий. Для генерации акселерограмм, соответствующих спектральным кривым, было разработано специализированное программное обеспечение. **Результаты.** Предложенный подход позволяет экстраполировать сильные акселерограммы на разные регионы Армении и использовать их при построении карт сейсмической опасности, включая распределение ускорений и спектры реакции. Данный подход повышает точность прогнозирования движений по сравнению с традиционными динамическими кривыми, лишёнными прямой эмпирической основы. Сгенерированные акселерограммы могут применяться при инженерном анализе, адекватной оценке опасности и уточнении нормативных документов сейсмостойкого проектирования. Несмотря на то, что методика разработана для Арменийских сейсмических норм (СН АР), она может быть адаптирована к другим международным стандартам, что расширяет ее значимость для мировой инженерной сейсмологии.

Ключевые слова: синтетические акселерограммы, оценка сейсмической опасности, спектры отклика, грунтовое усиление, Спитакское землетрясение, правила сейсмического проектирования, движения грунта совместимые со спектром.

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Introduction

The development of a set of computed accelerograms is a highly relevant and pressing issue, particularly in the seismically active region of the Republic of Armenia. This necessity arises due to the lack of a comprehensive strong-motion database. Notably, during the catastrophic Spitak earthquake on December 7, 1988 (M_w 7.0), it was

practically impossible to record accelerograms due to the extreme conditions of the event. During this earthquake, only a single accelerogram was recorded in the epicentral zone at the Gyukasyan station, where the PGA was measured at 0.21g (as shown in fig. 1). However, this isolated recording does not adequately represent the overall strong-motion characteristics of the event, highlighting the urgent need for a more robust database of strong earthquake records. These limitations highlight the necessity of seismic zonation maps for Armenia (see fig. 2).

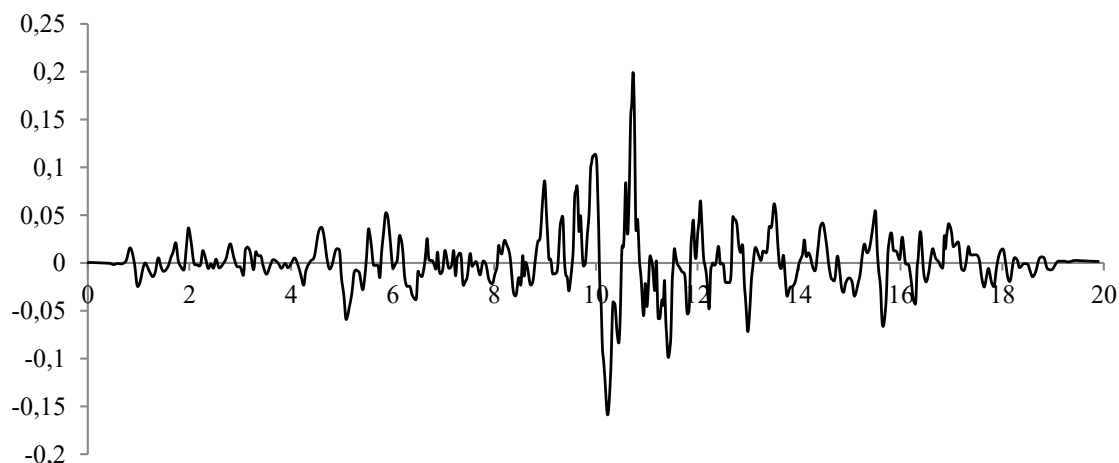


Fig. 1. Time-series plot of ground motion from the Spitak Earthquake (M_s 7.0, December 7, 1988). The x-axis represents time (0–20s), while the y-axis shows amplitude variations. A distinct peak around 10s indicates the main seismic event, followed by decaying oscillations

It is well known that during strong earthquakes, ground accelerations often exceed 0.4g. Given this, our objective is to generate computed accelerograms using records from relatively weak earthquakes in this region. These computed accelerograms will serve as a critical foundation for the development of seismic hazard assessment maps for the Republic of Armenia. This task is particularly significant because seismic hazard maps, expressed in fractions of g, have been compiled at different times for the territory of Armenia. These maps typically delineate three primary hazard zones, corresponding to peak accelerations of 0.3g, 0.4g, and 0.5g the regulatory classification of these hazard zones is summarized in table 2. By generating calculated accelerograms, we aim to enhance the accuracy and reliability of these assessments, contributing to more effective seismic risk mitigation strategies.

the highest hazard zones. Major fault lines and tectonic structures appear to influence these zones. By generating calculated accelerograms, the goal is to refine seismic hazard assessments, improving risk mitigation strategies for future earthquakes. The question of how the PGA (Peak Ground Acceleration) values were determined, which models of $PGA = f(M, R, V_s)$ were applied, and how their justification was established remains unresolved. Notably, the 2020 updated seismic construction standards incorporated a seismic hazard assessment map, delineating three primary hazard zones with PGA values of 0.3g, 0.4g, and 0.5g. These values were derived using international empirical models, whose accuracy is known to vary by a factor of up to two. This discrepancy is evident even when analyzing the PGA zonation, where Gyumri (formerly Leninakan) was assigned to Zone 2, while Vanadzor was categorized as Zone 3, the highest hazard level (see fig. 2). However, historical data from the 1988 Spitak earthquake contradicts this classification, as

damage was more severe in Leninakan than in Kirovakan (Vanadzor), a fact documented in the Unified Summary Report on the Spitak Earthquake (1988) (Scientific and technical report, Spitak earthquake of December 7, 1988 (in two parts), part II, IGES NAS RA funds 1990).

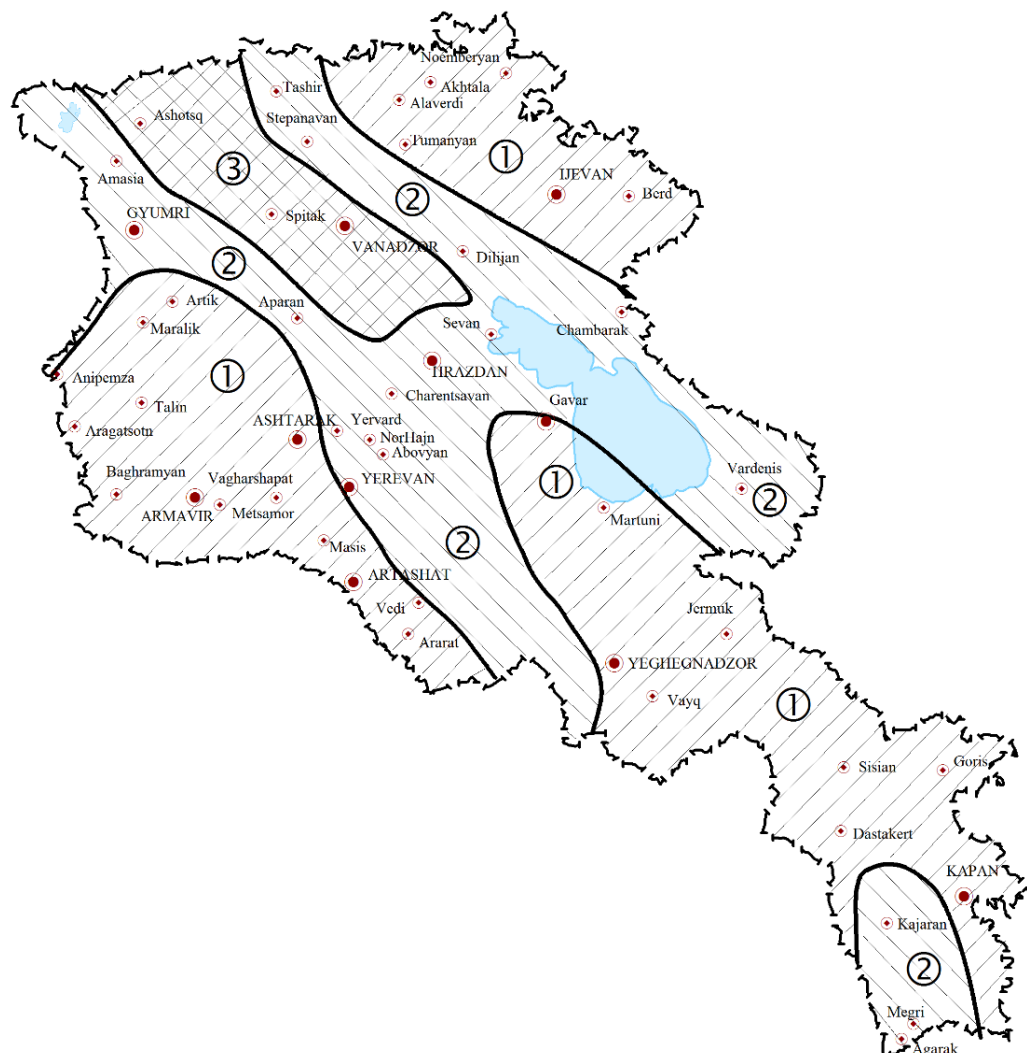


Fig. 2. Seismic hazard zonation map of Armenia by expected PGA values (0.3g, 0.4g, 0.5g)[BSRA ..., 2020]

The map represents seismic hazard zones in Armenia, categorized by expected peak ground accelerations of **0.3g, 0.4g, and 0.5g**. The shaded and numbered regions indicate varying levels of seismic risk, with darker or crosshatched areas likely representing Another noteworthy aspect of these standards is the inclusion of a dynamic curve (see fig. 3), which essentially represents a response spectrum. However, the spectrum values are presented as dimensionless quantities, essentially reflecting the ratio of the response spectrum to the peak acceleration value. Furthermore, the standards specify that seismic resistance calculations for buildings should be performed using computed accelerograms, yet no clear methodology is provided for how these calculations should be conducted. Given these uncertainties, we have set out to develop a comprehensive set of accelerograms based on response spectra, utilizing specific spectral curves (dynamic curves) as a foundation for our approach.

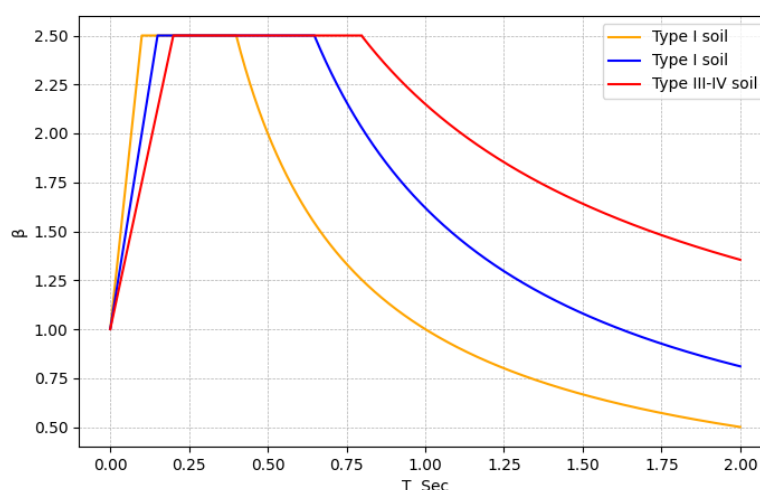


Fig. 3. Spectral amplification characteristics $\beta(T)$ for different soil types [BSRA ..., 2020]

The graph displays soil-dependent spectral amplification factors (β) as a function of period (T , in seconds). Three curves represent different soil types: For short periods ($T < 0.25$ s), as illustrated by the spectral amplification curves (see fig. 3 and table 1). All soil types show a rapid increase in β , reaching a plateau around $\beta=2.5$. For longer periods, the amplification factor decreases, with **Type III-IV soil** maintaining the highest values, followed by **Type II soil**, and **Type I soil** showing the steepest decline. The plot suggests that softer soils (Type III-IV) exhibit stronger amplification at longer periods, influencing seismic design considerations.

Table 1

Spectral amplification factor $\beta(T)$ for different soil types

Soil Type I	Soil Type II	Soil Type III-IV
$\beta = 1 + 15T$, when $0 < T < 0.1$ $\beta = 2.5$, when $0.1 \leq T \leq 0.4$ $\beta = \frac{1}{T}$, when $T \geq 0.4$	$\beta = 1 + 10T$, when $0 < T < 0.15$ $\beta = 2.5$, when $0.15 \leq T \leq 0.65$ $\beta = \frac{1.62}{T}$, when $T \geq 0.65$	$\beta = 1 + 7.5T$, when $0 < T < 0.2$ $\beta = 2.5$, when $0.2 \leq T \leq 0.8$ $\beta = \frac{1.622 \cdot 15}{T^{2/3}}$, when $T \geq 0.8$

From this spectrum, it is immediately apparent that within the period range of $T = 0.1$ – 0.8 sec, the amplitude levels remain identical across different soil conditions. This is inconsistent with reality, as no seismic standards utilize such curves where spectral amplitudes for different soil types remain at the same level. Moreover, the most intriguing aspect is how these curves were derived in the absence of strong motion recordings – a question that remains unresolved. The observed discrepancies can be attributed to the lack of a strong earthquake accelerogram database for the Republic of Armenia. Despite these shortcomings, at this stage of our research, we adopt these curves as a basis and conduct all subsequent analyses accordingly. Our research utilizes the only available strong motion record from the 1988 Spitak earthquake. Similar challenges in seismic hazard assessment have been reported in regional studies. For example, [Chernov, 2023, 2024] demonstrated the importance of spectral analysis in evaluating hazard levels. However, as is well known among seismologists and earthquake engineering specialists, this record does not fully represent the reality of seismic events of such magnitude. Nevertheless, our approach is highly flexible, allowing the incorporation of other strong

motion recordings. The selection of this particular record was intentional, as it presents an intriguing opportunity to examine how its application to normative spectral curves influences results. Specifically, we investigate the changes in the amplitude-frequency characteristics of waveforms and derive recommendations based on these findings. This is particularly significant for structural design, as high-rise buildings exceeding 16 floors rely on these standard spectral curves.

The response spectrum is a fundamental concept in evaluating the dynamic effects of earthquakes on civil engineering structures. Consequently, seismic design codes worldwide have adopted response spectra as a standard tool for defining design parameters. By ensuring that structures are designed to withstand seismic events with predefined spectral characteristics, this methodology provides an effective framework for earthquake-engineering. In practice, the irregular shape of real earthquake ground motion spectra is often smoothed for design applications [Chopra, 2017], providing a more uniform basis for structural analysis. This process typically involves assessing the response of various structural vibration modes while considering factors such as damping, ductility, and nonlinear behavior [Fardis, 2009; Priestley et al., 2007].

However, relying solely on response spectra may not provide a comprehensive structural assessment. While they are useful in many scenarios, response spectra do not fully capture complex behaviors such as damage progression, hysteretic deterioration, inelastic response, and second-order effects—critical factors in understanding the realistic performance of structures under seismic loads [Krawinkler, Seneviratna, 1998]. To address these limitations, time history analysis, which utilizes accelerograms, serves as a vital complement to response spectrum analysis [Saragoni, Hart, 1974]. Since real accelerograms often exhibit irregular spectra that may not align with code-defined design spectra, generating spectrum-compatible accelerograms has become essential in modern earthquake engineering [Al Atik et al., 2010].

Over the years, various methods have been developed to generate spectrum-compatible accelerograms. These methods generally fall into two categories: modifying recorded ground motions to match a target design spectrum or generating synthetic accelerograms from scratch [Gasparini, Vanmarcke, 1976]. Deterministic approaches employ harmonic superposition to create nonstationary signals [Li et al., 2021], while wavelet-based techniques modify recorded motions to conform to the required response spectrum [Chen et al., 2021]. Stochastic approaches, originally introduced by Vanmarcke and Gasparini [Vanmarcke, 1979; Gasparini, Vanmarcke, 1976; Rezaeian, Der Kiureghian, 2010] model accelerograms as Gaussian processes, establishing a link between the response spectrum and the power spectral density function. More recently, artificial intelligence techniques, such as neural networks, have been explored for generating spectrum-compatible accelerograms. In addition to classical approaches [Saragoni, Hart, 1974], several recent studies have introduced advanced techniques for generating spectrum-compatible accelerograms, including Matlab-based codes [Ferreira et al., 2020], wavelet-based methods [Ferreira et al., 2020; Li et al., 2021], stochastic multi-step approaches [Dabaghi, Der Kiureghian, 2017; Vanmarcke, 1979]; neural networks and iterative schemes accounting for site effects [Huang, Wang, 2017].

In this paper, we introduce a method for generating spectrum-compatible accelerograms, specifically tailored to the Armenian Seismic Code. Our approach modifies recorded ground motion data to align with target design spectra. The method involves computing the initial response spectrum and using Fourier transforms to adjust the frequency content

of the ground motion until the final accelerogram matches the design spectrum. This technique provides an efficient and accessible tool for researchers and practitioners, easily integrating into Python programs or other seismic analysis software. By offering this tool, we aim to facilitate its application in nonlinear structural analysis and seismic control systems while ensuring compliance with the updated requirements of the Armenian seismic code.

Methods

Response spectra determination differential equation solver

The response spectrum is defined as the peak response of a single degree-of-freedom structure with different natural frequencies for a specified damping coefficient ζ subject to a given ground accelerogram $\ddot{u}_g(t)$. To determine the response spectra, the following steps need to be performed:

- Specify the natural period range P to be analyzed and determine the corresponding natural angular frequencies ω ($\omega = 2\pi/P$);
- For all frequencies ω within the range, solve the dynamic differential equation (Equation 1) in the time domain (t).
- The acceleration response spectra are then defined as the maximum structural response for the given accelerogram and for each period $S_a(P) = \text{Max}|\ddot{u}_t|$

The acceleration response spectra are the most commonly used for structural design and, for this reason, will be used in this work.

$$\ddot{u}(t) + 2\xi\omega\dot{u}(t) + \omega^2u(t) = -\ddot{u}_g(t) \quad (1)$$

where, $u(t)$ is the time-dependent structural displacement.

Considering the state space formulation using the vector x defined as $x = \begin{bmatrix} u \\ \dot{u} \end{bmatrix}$, the second-order equation (Equation 1) is replaced with a first order:

$$\dot{x} = Ax + B\ddot{u}_g \quad (2)$$

The matrices A and B are defined by

$$x = \begin{bmatrix} u \\ \dot{u} \end{bmatrix}, A = \begin{bmatrix} 0 & I \\ -\omega^2 & -2\xi\omega \end{bmatrix}, B = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (3)$$

where, I is the identity matrix.

The dynamic equation has an analytical solution for a given time step Δt .

$$x(t + \Delta t) = e^{\Delta t A}x(t) + \int_t^{t+\Delta t} e^{[(t+\Delta t)-\zeta]A}B\ddot{u}_g(\zeta)d\zeta \quad (4)$$

Assuming that the ground acceleration has a linear variation within each time step, the dynamic time history analysis can be performed using the following equation:

$$x(t + \Delta t) = K_b x(t) + K_b B \ddot{u}_g(t) + K_{\Delta f} B [\ddot{u}_g(t + \Delta t) - \ddot{u}_g(t)] \quad (5)$$

were

$$K_b = e^{\Delta t A}; K_f = A^{-1}(K_b - I); K_{\Delta f} = A^{-1}(K_f - I) \quad (6)$$

Code-defined response spectra in accordance with Armenian seismic norms

The formulation of the response spectrum is a fundamental component of seismic

hazard assessment, providing a quantitative framework for evaluating the seismic demand on structures. In this study, the spectral definition adheres to the Armenian Seismic Construction Norms [Armenian Seismic Norms 20.04-2020], which prescribe seismic design spectra based on probabilistic seismic hazard analysis, local soil conditions, and structural characteristics. These norms replace the Eurocode 8 (EC8) (EN 1998-1:2004 + A1:2013 (Eurocode 8). Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings. Brussels. CEN. 231 p.) classification and introduce a region-specific methodology for defining seismic response spectra.

Seismic hazard classification

Armenian seismic regulations categorize the seismic hazard level into three seismic zones, each associated with a predefined peak ground acceleration (PGA):

$$a_g = \begin{cases} 300 \text{ cm/s}^2, & \text{for Zone 1} \\ 400 \text{ cm/s}^2, & \text{for Zone 2} \\ 500 \text{ cm/s}^2, & \text{for Zone 3} \end{cases}$$

These values correspond to a 475-year return period with a 10% probability of exceedance within a 50-year timeframe, consistent with international seismic risk assessment practices.

Soil classification and site-specific seismic amplification

Unlike EC8, which defines five soil categories (A–E), the Armenian seismic norms classify soils into four categories (I–IV) based on shear wave velocity (V_s), dynamic response properties, and geotechnical characteristics. A detailed description of soil categories, shear wave velocities, and examples is provided in table 2 and 3.

Table 2

Seismic hazard zones of Armenia and corresponding PGA values according to Norms 20.04-2020 [BSRA ..., 2020]

Soil Type	Description	Shear Wave Velocity V_s (m/s)	Examples
I	Hard rock, igneous formations	$V_s \geq 850$	Igneous rock, dense formations
II	Stiff to medium-dense soil	$450 \leq V_s < 850$	Dense sands, gravels, weathered rock
III	Soft soil deposits	$180 \leq V_s < 450$	Loose sands, soft clays, alluvial deposits
IV	Very soft soils prone to liquefaction	$V_s < 180$	Peat, organic clay, saturated sediments

This table defines the seismic hazard zones prescribed by Armenian Seismic Norms (Armenian Seismic Norms 20.04-2020). The peak ground acceleration (PGA) values correspond to a 475-year return period with a 10% probability of exceedance in 50 years. The PGA values are assigned based on the region's seismic hazard classification, which is divided into three zones. For sites with significant stratigraphic variation, the effective site classification is determined based on the weighted average shear wave velocity over the upper 30 meters of soil, following:

$$V_{s30} = \frac{H}{\sum_{i=1}^n \frac{h_i}{V_{s,i}}} \quad (7)$$

where: H is the total thickness of the soil layers (30 m), h_i and $V_{s,i}$ are the thickness and shear wave velocity of the i -th layer.

Seismic response spectrum formulation

The spectral acceleration function in the Armenian norms follows the standard form:

$$S_a(T) = A \cdot k_0 \cdot \beta(T) \cdot g \quad (8)$$

where: A is the seismic hazard factor corresponding to the designated seismic zone, k_0 is the soil amplification coefficient that accounts for local site effects, $\beta(T)$ is the dynamic amplification function, which depends on the fundamental period T of the structure, g is the acceleration due to gravity. The soil amplification coefficient k_0 modifies the peak ground acceleration according to the local soil conditions:

Table 3

**Soil classification in Armenian Seismic Norms (20.04-2020)
with amplification coefficients**

Soil Type	Seismic Zone 1	Seismic Zone 2	Seismic Zone 3
I (Rock)	0.8	0.8	0.8
II (Dense sand/gravel)	1.0	1.0	1.0
III (Medium-density clays)	1.1	1.0	1.0
IV (Soft, water-saturated soil)	1.2	1.1	1.0

This scaling factor ensures that soft soils amplify seismic motion to a greater extent than stiff soils, in accordance with empirical ground motion records and theoretical site response models. For each soil type, a specific amplification function $\beta(T)$ is used:

$$\beta(T) = \begin{cases} 1 + \frac{T}{T_B}, & 0 \leq T < T_B \\ \beta_0, & T_B \leq T \leq T_C \\ \beta_0 \frac{T_C}{T}, & T_C \leq T \leq T_D \end{cases}$$

where: T_B, T_C, T_D , define spectral shape regions per soil type, β_0 is the maximum spectral amplification factor, which varies between 2.5 and 3.5.

Structural damping considerations

In line with standard seismic engineering practices, Armenian norms adopt a viscous damping ratio of $\xi=5\%$ as the reference value for response spectrum calculations. The damping-adjusted spectral modification is applied using a correction function:

$$\eta(\xi) = \sqrt{\frac{10}{5+\xi}} \quad (9)$$

where $\eta(\xi)$ accounts for the influence of damping on spectral ordinates, ensuring compliance with realistic structural damping behavior.

Seismic Event Characterization: Near-Field vs. Far-Field Earthquakes

While EC8 differentiates between Type 1 (far-field) and Type 2 (near-field) earthquakes,

Armenian norms implicitly incorporate earthquake duration and site-specific spectral adjustments. The duration of synthetic accelerograms is prescribed as follows:

$$T_d = \begin{cases} 20s, & \text{for Zone 1} \\ 25s, & \text{for Zone 2} \\ 30s, & \text{for Zone 3} \end{cases}$$

This criterion ensures that seismic simulations account for the longer ground shaking duration associated with higher seismic hazard zones, aligning with empirical earthquake recordings.

Based on table 3, the soil-condition coefficients k_0 vary in the first seismic zone (PGA = 0.3g). In the second zone, k_0 changes only for Soil Category IV (to 1.1). In the third and most severe zone (PGA = 0.5 g), the coefficients are left unchanged $k_0 = 0.8$ for Category I and $k_0 = 1.0$ for all other categories. This pattern appears ad hoc, seemingly to prevent the design acceleration from exceeding 0.5g.

A second concern is the assigned durations of the artificial accelerograms 20 sec for Zone 1, 25 sec for Zone 2, and 30 sec for Zone 3. This approach is questionable, because the duration of strong motion in damaging earthquakes spans a broad range. Since these choices directly affect the design of earthquake-resistant buildings and structures, both the coefficients and the durations should be re-examined and replaced with values that better represent actual strong-motion behavior, taking into account not only local site conditions but also the general characteristics of large earthquakes.

Artificial accelerogram generator

Algorithm fundamentals

The generation of an artificial accelerogram to match code-defined spectra (either based on the modification of real or synthetic accelerograms) can be stated as an optimization problem in which the response spectra are to be matched as close as possible to the defined spectra. The wavelet-based formulations proposed by [Ferreira et al., 2020; Li et al., 2021] provide additional justification for the use of time-frequency domain methods in developing spectrum-compatible accelerograms. In order to solve the problem, it is representative to use the Fourier Transform in order to have the frequency content of the signal. The Fourier Transform $\ddot{U}_g(\omega)$ of the time history function $\ddot{u}_g(t)$ is defined as:

$$\ddot{U}_g(\omega) = \int_{-\infty}^{\infty} \ddot{u}_g(t) e^{-i\omega t} dt \quad (10)$$

The response spectra in a given frequency ω (or period P) can be stated as being proportional to the power a of the Fourier Transform value at the same frequency. The value of k and α are heavily dependent on the type of earthquake:

$$S_a(\omega) \propto k \ddot{U}_g(\omega)^\alpha \quad (11)$$

For very high frequencies, the response spectra converge to the value of the PGA:

$$\lim_{\omega \rightarrow \infty} S_a(\omega) = \max |\ddot{u}_g(t)| \quad (12)$$

To match the code-defined response spectrum, the Fourier amplitude spectrum is iteratively modified using the ratio of the **target** and **computed** response spectra:

$$\tilde{U}_g^{(n+1)}(\omega) = \tilde{U}_g^{(n)}(\omega) \cdot \frac{S_a^{target}(\omega)}{S_a^{computed}(\omega)} \quad (13)$$

Where S_a^{target} is the response spectrum of the current iteration, $S_a^{computed}$ is the Armenian design spectrum.

Finally, an **inverse Fourier transform (IFFT)** reconstructs the modified accelerogram:

$$\ddot{u}_g^{(n+1)}(t) = \mathbf{F}^{-1} \left\{ \tilde{U}_g^{(n+1)}(\omega) \right\} \quad (14)$$

This iterative process continues until the convergence criterion is satisfied, namely

$$\max \left| \frac{S_a^{computed}(T) - S_a^{target}(T)}{S_a^{target}(T)} \right| < 5\% \quad (15)$$

which ensures that the final artificial accelerogram is spectrum-compatible according to the Armenian Seismic Norms 20.04-2020.

A frequency-dependent soil propagation model

The propagation of ground vibrations through soil is governed by complex interactions between geometric attenuation and material damping. Geometric attenuation results from the natural spreading of wave energy as it propagates outward, while material damping accounts for energy dissipation due to the internal friction and viscoelastic behavior of the soil. This paper presents a frequency-dependent soil propagation model that incorporates both attenuation mechanisms, enabling precise estimation of vibration transmission for engineering and seismological applications.

Ground vibrations propagate through Rayleigh (surface) waves and body waves (shear and compressional waves). The general expression describing the attenuation of vibration amplitude from a source at distance r_a to a receiver at distance r_b is:

$$v_b = v_a \left(\frac{r_a}{r_b} \right)^\gamma e^{\alpha(r_a - r_b)} \quad (16)$$

Where v_a and v_b are the vibration velocities at points a and b, respectively, γ is the geometric attenuation coefficient, which varies depending on wave type, α is the material damping coefficient, which accounts for energy dissipation.

Geometric attenuation occurs due to wavefront expansion as the energy propagates outward. The coefficient γ depends on the wave type and can be determined from theoretical models of wave radiation in an elastic half-space. For common vibration propagation scenarios, the values of γ are summarized in Table 4. These values have been validated through experimental measurements and empirical studies in vibration control, seismic wave analysis, and construction engineering, such as those by [Richart et al., 1970; Barkan, 1962; Dowding, 1996]. They are widely used in engineering practice for modeling vibration propagation and predicting the impact of ground motion on structures.

Rayleigh waves, which dominate surface propagation, exhibit the lowest attenuation ($\gamma=0.5$), corresponding to 3 dB per doubling distance. Body waves attenuate more rapidly, with surface measurements showing $\gamma=2.0$ (12 dB per doubling distance) and depth measurements yielding $\gamma=1.0$ (6 dB per doubling distance). These coefficients are essential for modeling ground vibration propagation, particularly in site-specific assessments (table 4).

Table 4

Theoretical geometric attenuation coefficients (γ) for different wave types and measurement locations

Wave Type	Measurement Location	γ	Attenuation (dB/doubling distance)
Rayleigh Waves	Surface	0.5	3
Body Waves	Surface	2.0	12
Body Waves	Depth	1.0	6

The attenuation due to geometric spreading is expressed in logarithmic form as:

$$A_\gamma = 20_\gamma \log_{10} \left(\frac{r_a}{r_b} \right) \quad (17)$$

Material damping describes energy dissipation mechanisms within the soil, primarily due to internal friction and hysteretic behavior. Several damping parameters are commonly used in engineering and geophysics, including the loss factor (η), the damping ratio (ζ), the resonance amplification factor (Q), and the logarithmic decrement (δ). These parameters are related by the following expressions:

$$\eta = 2\zeta = \frac{\delta}{\pi} = \frac{1}{Q} \quad (18)$$

Richart, Hall and Woods [1970] define the relationship between α and these material coefficients as shown in

$$d = \frac{2\rho c a}{w} = l a = \frac{c a}{f} \quad (19)$$

The material damping coefficient α is related to these damping parameters by:

$$\alpha = \frac{h \rho f}{c} \quad (20)$$

Where f is the vibration frequency (Hz) c is the wave velocity in the medium. Since η and c are often assumed constant for a given soil type, a soil-specific attenuation parameter is introduced:

$$\rho = \frac{\eta}{c} \quad (21)$$

which allows the material damping coefficient to be rewritten as:

$$\alpha = r \rho f \quad (22)$$

Woods and Jedgele [Woods, Jedgele, 1985] have proposed a classification of soil by attenuation coefficient. A comparative overview of soil types and their attenuation parameters is given in table 5. [Dowding, 1996] summarizes this in terms of ranges of α at 5 Hz and 50 Hz, but if one uses Equation (22) as a definition of α , one can arrive at a tabulation of ρ as a function of earth material type. This is given in table 5. The constant ρ can be used in propagation models of the form given in Equation (23).

$$\frac{V_b}{V_a} = \left(\frac{r_a}{r_b} \right)^g e^{r \rho f (r_a - r_b)} \quad (23)$$

The vibration attenuation (in dB) between points “a” and “b” can be stated in the form of Equation (24).

$$\text{Attenuation} = VL_b - VL_a = 20 \log \left(\frac{v_b}{v_a} \right) \quad (24)$$

This formulation highlights the frequency dependence of attenuation, showing that higher-frequency components decay more rapidly than lower-frequency components. The total attenuation between two points a and b can be expressed as the sum of geometric attenuation and material damping:

$$\text{Attenuation (A)} = A_\gamma + A_\alpha \quad (25)$$

where:

$$A_\alpha = 8.68 \times \alpha \times (r_a - r_b) \quad (25a)$$

$$A_\gamma = 20 \times \gamma \times \log_{10} \left(\frac{r_a}{r_b} \right) \quad (25b)$$

This equation explicitly accounts for both distance-dependent and frequency-dependent attenuation, making it applicable for practical engineering assessments and site-specific vibration modeling. The factor 8.68 in the attenuation equation converts the natural exponential decay into decibel (dB) form, facilitating the use of the material damping coefficient (α) in vibration attenuation models expressed in dB. This conversion aligns with standard practices in vibration engineering and geophysics.

Measurement of site-specific attenuation

To determine the site-specific damping ρ , the following procedure is followed:

1. Field Measurements: Vibration spectra are recorded at two distances r_a and r_b from a known source.

2. Transfer Function Calculation: The spectral difference (in decibels) between the two measurement points is computed.

3. Geometric Attenuation Subtraction: The term A_γ is subtracted from the transfer function.

4. Material Damping Extraction: The remaining attenuation component is attributed to material damping and used to solve for ρ :

$$r = \frac{a}{\rho f}$$

5. Attenuation Curve Construction: The frequency-dependent attenuation curve is generated using:

$$A_\alpha = 8.68 r \rho f (r_b - r_a)$$

6. Validation and Model Fit: The measured data is compared against the theoretical attenuation curve to ensure consistency.

Table 5

Soil classification by attenuation coefficient α and correspondence with Armenian seismic norm categories

Seismic Soil Classification (Armenian Seismic Norms 20-04-2020)	Description of Material	Attenuation Coefficient α (ft^{-1} at 5 Hz)	ρ (Soil Property Parameter)
I – Rock formations, igneous and metamorphic bedrock	Hard, competent rock: bedrock, fresh solid rock	< 0.0001	$< 6 \times 10^{-6}$
II – Dense sands, weathered rock, well-compacted soils	Hard soils: dense sand, consolidated clay, glacial till	$0.0001-0.001$	$6 \times 10^{-6} - 6 \times 10^{-5}$
III – Medium-density sands and silty clays, compacted fill	Competent soils: silty clays, sandy clays, gravel, weathered rock, compacted fill	$0.001-0.003$	$6 \times 10^{-5} - 2 \times 10^{-4}$
IV – Soft, water-saturated sands, organic soils, loess	Weak or soft soils: loose sand, loess, peat, recently plowed ground, organic soils, topsoil	$0.003-0.01$	$2 \times 10^{-4} - 6 \times 10^{-4}$

Table 5 provides an overview of soil classifications based on their attenuation properties and correlates them with the seismic soil classifications from the Armenian seismic construction norms (Armenian Seismic Norms 20-04-2020). The aim is to integrate **geophysical attenuation coefficients** with **engineering soil categories**, making it easier to apply in practical seismic hazard assessments.

Results and Discussion

The following section presents the main results obtained from the generation of spectrum-compatible artificial accelerograms and their comparison with the existing Armenian seismic norms. The calculated ground motions are analyzed across different soil categories (I–IV), and their spectral characteristics are compared with code-defined response spectra. Special attention is given to the discrepancies identified between the current regulatory maps of peak ground acceleration (PGA) and the actual damage distribution observed during the 1988 Spitak earthquake. The discussion highlights both the applicability of the proposed methodology and its limitations, providing a critical basis for improving seismic hazard assessment and updating design regulations. This discrepancy between normative PGA maps and actual earthquake damage has also been discussed in regional studies [Zaalishvili et al., 2022, 2024; Chernov, 2023; Fidarova et al., 2023], confirming the necessity of updating hazard assessments based on both empirical evidence and simulated motions.

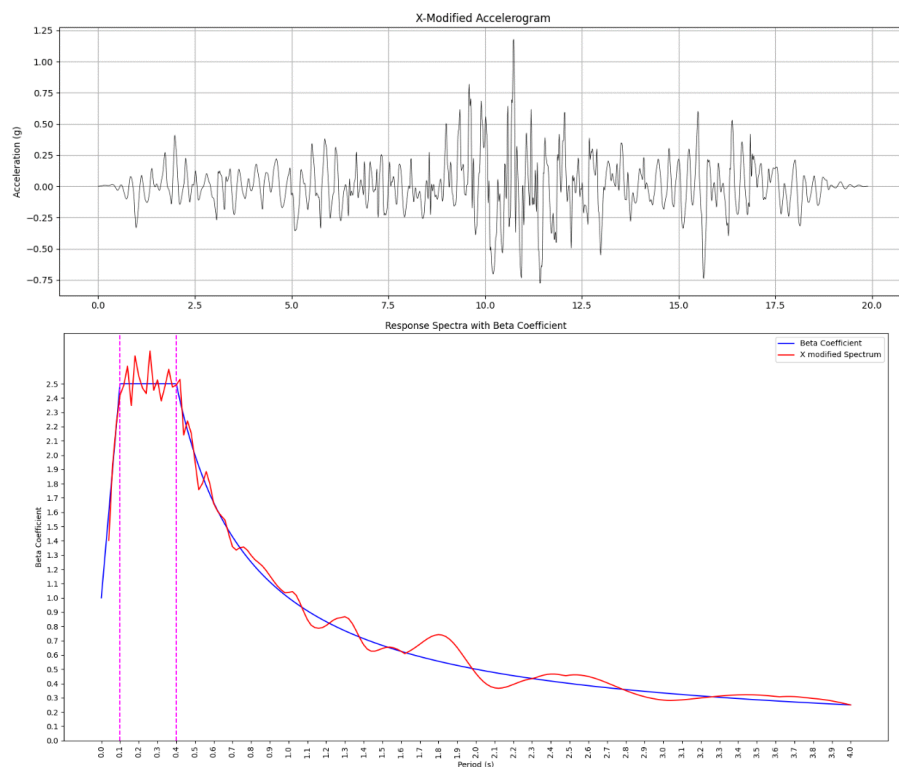


Fig. 4. Modified seismic response of the 1988 Spitak Earthquake for Soil Type I

The adjusted response for Soil Type I is shown in fig. 4, while results for Soil Type II and Soil Types III–IV are presented in fig. 5 and fig. 6, respectively.

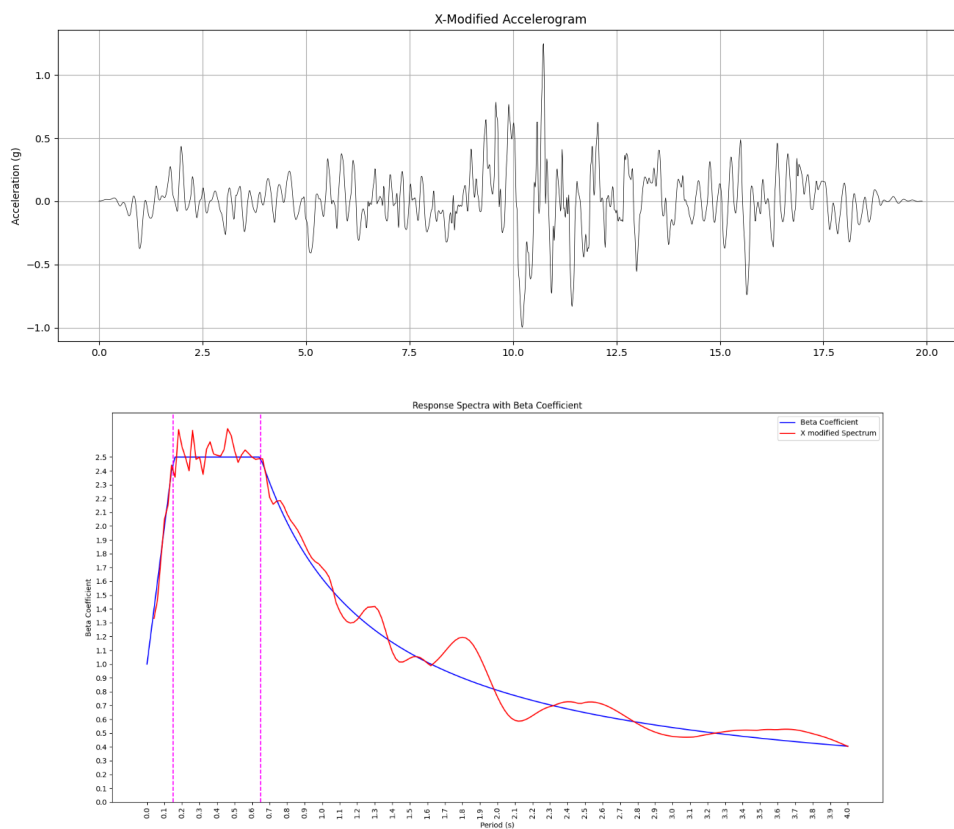


Fig. 5. Modified seismic response of the 1988 Spitak Earthquake for Soil Type II

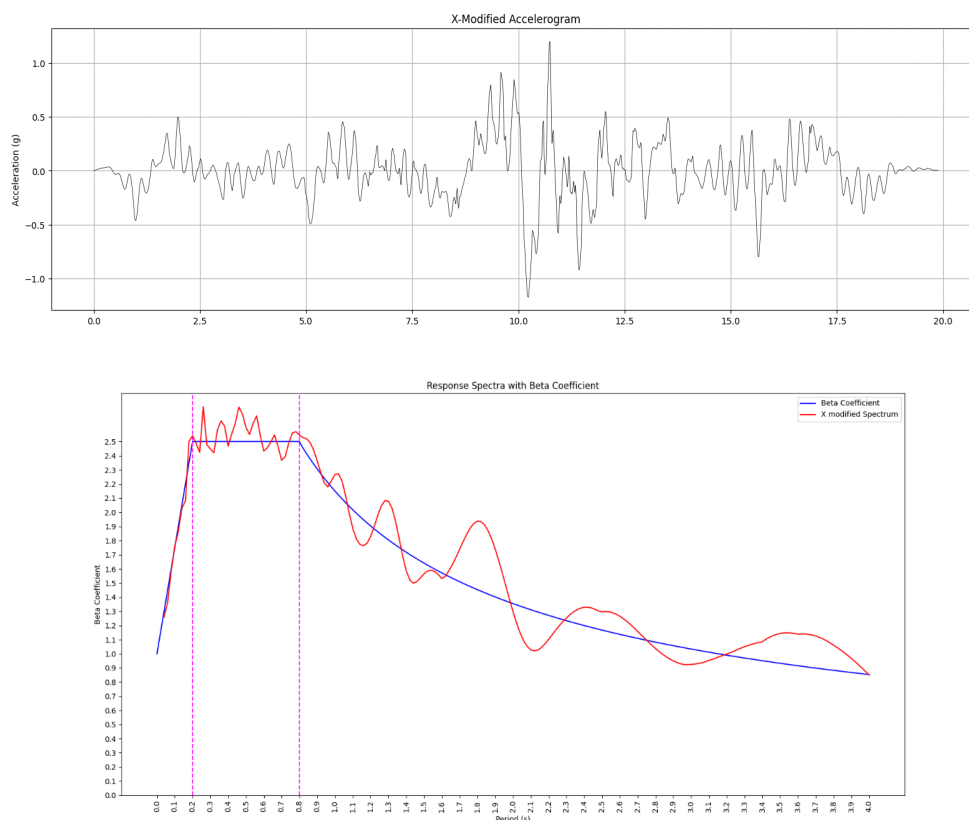


Fig. 6. Modified seismic response of the 1988 Spitak Earthquake for Soil Types III–IV

The vibration analysis of advanced technology facilities must account for both the frequency and amplitude of vibrations. A soil propagation model has been developed to incorporate site-specific, measurable, frequency-dependent attenuation characteristics. Additionally, a method has been introduced for the in-situ determination of these frequency-dependent properties, enabling more accurate assessment of vibration behavior. Comparable results have been obtained in stochastic modeling approaches, such as the multi-step framework proposed by [Dabaghi, Der Kiureghian, 2017], which showed that soil-dependent amplification can significantly affect the spectral response.

Conclusion

A new approach to calculating artificial accelerograms based on spectral normative curves corresponding to different soil categories is proposed. Based on these calculations, the only record of strong movements of the Spitak 07.12.1988 earthquake on the territory of the Republic of Armenia was laid down. What is important is that the obtained calculated records differ not only in amplitude, but also in the frequency of appropriateness for soft and hard soils. In the future, when accumulating accelerograms of earthquakes of medium strength starting from 3.5 magnitudes, this method can be used to obtain accelerograms of strong movements in different areas of the territory of the Republic of Armenia for different categories of soils. These results allow us to obtain calculated accelerograms close to reality, which can be used to compile not only new normative maps, but also to obtain new spectral curves, and in the future to use more accurate normative curves, and not some dynamic curves presented as spectral curves. These findings are directly related to the refined hazard maps and spectral response curves (see fig. 2 and fig. 3). Based on

these results, software was developed that allows one to obtain calculated accelerograms based on spectral curves and which can be used to calculate buildings and structures of various structural systems. Additionally, we conducted a focused review of selected standards provisions that are especially critical for seismic building design. The article provided some valuable critical discussions that could be taken into account in the future when drafting new regulations. The methodology for computing artificial accelerograms follows a multi-step approach integrating spectral normative curves, stochastic simulation techniques, and validation against observed seismic records. The process consists of the following key stages:

The spectral acceleration values are defined for different soil types, considering soil amplification factors derived from empirical ground motion models and local seismic norms. The curves incorporate site-specific modifications to ensure a realistic representation of the seismic response across various geological conditions. The Fourier transform is applied to match the frequency content of the synthetic waveforms with the prescribed response spectra. The importance of including site effects in accelerogram generation was also emphasized in recent work by [Huang, Wang, 2017], who demonstrated that frequency-dependent attenuation models improve compatibility with observed response spectra. The findings are consistent with recent advances in spectrum-compatible ground motion generation [Ferreira et al., 2020; Huang, Wang, 2017], confirming that the proposed methodology aligns with international trends and can be adapted for broader applications. This iterative frequency-domain modification ensures that the final accelerogram is spectrum-compatible while preserving realistic ground motion characteristics. A computational tool was developed to automate the generation of spectrum-compatible accelerograms, integrating the proposed methodology into a software framework. This tool allows for site-specific seismic analysis, enabling engineers to perform nonlinear structural assessments based on computed ground motions. The software ensures compliance with the Armenian Seismic Code while allowing adaptability to international seismic standards.

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