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Review

The Importance of Assessing the Geological Site Effects of Ancient Earthquakes from the Archaeoseismological Point of View

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Abstract: Earthquakes have and continue to, occur worldwide, though some places are affected more than others by earthquake-induced ground shaking and the same earthquake can cause more damage in one area than in nearby locations due to site-specific geological site conditions, also known as local site effects. Depending on the chronology of the earthquakes, various disciplines of seismology include instrumental and historical seismology, archaeoseismology, palaeoseismology and neotectonics, each focusing on using specific sources of information to evaluate recent or ancient earthquakes. Past earthquakes are investigated to expand the pre-instrumental and instrumental earthquake catalog and better evaluate a region's seismic hazard. Archaeoseismology offers a way to achieve these goals because it links how ancient civilizations and their environment might have interacted and responded to past earthquake-induced ground motion and soil amplification. Hence, archaeoseismology explores pre-instrumental (past) earthquakes that might have affected sites of human occupation and their nearby settings, which have left their co-seismic marks in ancient manufactured constructions exhumed by archaeological excavations. However, archaeoseismological observations are often made on a limited epicentral area, poorly constrained dated earthquakes and occasionally on unclear evidence of earthquake damage. Archaeological excavations or field investigations often underestimate the critical role that an archaeological site's ancient geological site conditions might have played in causing co-seismic structural damage to ancient anthropogenic structures. Nevertheless, the archaeological community might document and inaccurately diagnose structural damage by ancient earthquake shaking to structures and even estimate the size of past earthquakes giving little or no consideration to the role of geological site effects in addressing the causative earthquake. This mixture of factors frequently leads to imprecise estimates of the size of ancient earthquakes and unlikely earthquake environmental impacts, leaving unexplained the location and the moment magnitude of the causative earthquake. Hence, it is essential not to rely solely on earthquake intensities based on archaeologically documented co-seismic damage without assessing the nature of the observed structural damage and the contribution of the geological site effects. This paper explains the geological site effects concept to archaeologists unfamiliar with the notion. It clarifies its role in assessing ground shaking, soil amplification and earthquake intensity by past earthquakes and how and why the geological site effects can be estimated when a site is thought to have been struck by an earthquake. Hence, the geological site effects must be considered when archaeological excavations describe and interpret destruction layers. Conversely, engineers and seismologists dealing with seismic hazard risk assessment must pay close attention to archaeological investigations assessing earthquake intensities and locations based on field evidence of damage to structures attributed to past earthquakes, because the geological site effects might have been factored in inaccurately or not at all.

Keywords: ancient earthquakes; local site effects; forward numerical modeling

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1. Introduction

Earthquakes are vibrations within the Earth resulting from the rupture and sudden movement of rocks that have been strained beyond their elastic limit and have released the accumulated strain [1,2]. The sudden release of seismic energy, caused by the rapid motion along a geological fault, generates seismic waves that shake the ground. Earthquakes can occur in the crust and even deeper into the mantle. However, areas near tectonic plate boundaries are more prone to ground shaking. Earthquakes repeatedly occur globally, yet some places are affected more than others and the same earthquake can cause more damage in one area than in its nearby locations. Destructive earthquakes typically happen over centuries and millennia but the record of instrumentally documented earthquakes spans no more than a century, leading to a short record or catalog of instrumental earthquakes. In the last ten years, mitigation plans have been built based on seismic micro-zonation studies worldwide [3]. In order to decrease the seismic hazard of a region and prepare proper mitigation plans, a longer record of earthquakes is required than can be provided instrumentally [4]. Identifying and studying ancient earthquakes is the key to expanding the earthquake catalog of a region. Ancient earthquakes are those events that pre-date the instrumental-earthquake period and can only be identified through direct evidence in the archaeological or geological record by the fields of archaeoseismology and palaeoseismology, respectively [4–8].

Archaeological excavations or investigations might be the first efforts to reveal structural damage to anthropogenic structures. When an archaeological site is near or within a seismically active region, it is tempting to attribute the observed structural damage to an earthquake. However, the damage might be due to other causes. The method of assessing the cause of destruction requires seismological and engineering insights. In principle, the critical role of the geological site conditions during earthquake-induced ground motion remains to be understood in the archaeological community. The aim of this paper is two-fold: (1) to communicate to the archaeological community the importance of the geological site effects concept on ancient earthquake-induced ground shaking and soil amplification estimations for archaeological sites and (2) to explain how and why the geological site effects can be estimated when a site is thought to have been affected by such natural phenomena. In addition, modern seismic site response estimations for micro-zonation studies should continue to look for ancient earthquakes documented in an archaeoseismological context, not just in an archaeological one.

2. Geological Site Effects

For a long time, earthquake records have shown that surface ground motions recorded at a given site can vary noticeably even over small inter-site distances [9–14]. Ground shaking and possibly induced structural damage to manmade structures are strongly influenced by the rupture mechanism of an earthquake source, the effects of the path traveled by seismic waves and the surface and underground structure of the site where the ground motion is recorded. Each of these three elements (i.e., source, path and site) is a seismological topic and has been investigated by experts in the field for many years (e.g., [11,14–17]).

When a geologic fault ruptures below the Earth's surface, seismic energy radiates from the earthquake source in a spherical pattern; however, the radiation pattern of a shear rupture is non-spherical. These body waves are refracted and reflected when they reach the interface between geologic materials with different seismic wave velocities. Therefore, when the seismic rays reach the ground surface, multiple refractions have often bent the seismic rays to a nearly upright direction [18] (Figure 1). Even though seismic waves might travel through tens or hundreds of kilometers in the Earth's crust and often less than 100 m of soil, the soil deposit strongly influences the characteristics of the ground surface motion [18].

The underground geologic structure, consolidation, variation of the groundwater table, variation of material mechanical properties in the near-subsurface, in addition to the presence of heterogeneities and discontinuities and surface topography can influence amplitude (may amplify or de-amplify motion), the frequency content (may shift to higher or lower) and the duration of strong shaking [14,18–24]. The amplification of seismic waves is due to crest or valley effects as well as the impedance contrast between horizontally layered sediments and overlying soils (lower impedance) and the underlying bedrock (higher impedance) (Figure 1) [22,25]. Soil response depends on the soil's type, thickness and stiffness. Recognized as the subject of intensive investigation for many years, this concept is referred to as "*local site effects*" [11,14] or its equivalent term, "*geological site effects*". The geomorphologic conditions that influence the local site response are illustrated schematically in Figure 2, following the categorization of Panzera et al. [26].

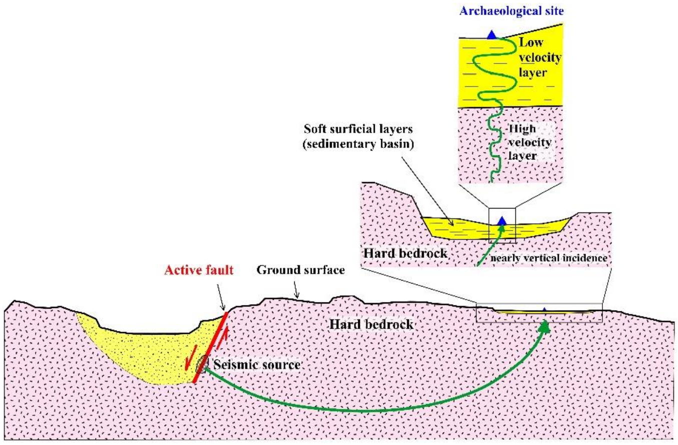

Figure 1. (Lower panel) Refraction processes that produce steep incidence of a seismic wave near the ground surface. (Middle and Upper panels) Zoomed areas where seismic wave amplification occurs due to the transition from higher velocity rock (higher impedance) to lower velocity sediments (lower impedance). Modified with permission from [18]. Copyright 2016, Hinojosa-Prieto, H.R.

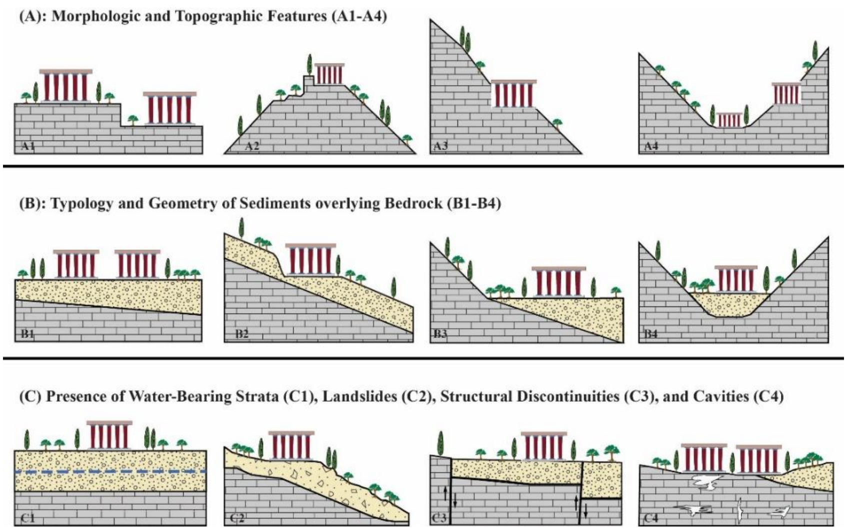

Figure 2. Sketch illustrating the conceptualized main geomorphologic categories (**A**–**C**) with the corresponding possible scenarios (sub-categories (**A1**–**C4**), respectively) for local site response. (Adapted with permission from Ref. [25]. Copyright 2013, Panzera et al.). The black arrows in C3 indicate a fault and its direction of motion.

Seismic ground motion and related ground amplification are significant factors influencing the degree of damage to infrastructure [11,13,27–29]. A typical scenario of seismic wave amplification occurs during the seismic loading of soil deposits that overlie relatively more rigid bedrock [22,30–32]. Some well-known examples of ancient and instrumental earthquakes worldwide with observable geological site effects are listed in Table 1. A sequence of earthquakes can also induce seismic ground motion and soil amplification, as illustrated by central Italy's well-documented and discussed 2016 earthquake sequence [33].

Nowadays, earthquake engineering practice requires the estimation of the level of ground motion and ground amplification for a given site to assess the seismic vulnerability of infrastructure and the susceptibility of soils during future earthquakes [22,28,34–38]. Nevertheless, the evaluation of geological site effects is relatively sparse in quantitative archaeoseismology. Examples of archaeoseismic investigations considering local site effects include [39–49].

Table 1. Some well-documented damaging earthquakes with observable geological site effects. (Modified with permission from [18]. Copyright 2016, Hinojosa-Prieto, H.R.).

Event	Magnitude	Depth (km)	Reference
1703 Central Italy earthquake	M_w = 6.7	?	[50]
1749 Northern Colima Graben, Mexico earthquake	M_w = 6.7	?	[51]
1938 Northern Belgium earthquake	M_s = 5.0	19 ± 4	in [18]
1906 San Francisco, California earthquake	M_w = 7.9	10.0	in [18]
1970 Ancash, Peru earthquake	M_w = 7.9	13.0	earthquakes.usgs.gov
1909 NW Peloponnese Greece earthquake	M_w = 5.9	?	[52]
1985 Michoacán, Mexico earthquake	M_s = 8.1	17.0	in [18]
1989 Loma Prieta, California earthquake	M_s = 7.1	12.0	in [18]
1994 Northridge, California earthquake	M_w = 6.7	17 ± 1	in [18]
1995 Kobe, Japan earthquake	M_w = 6.9	17.0	in [18]
1999 Athens, Greece earthquake	M_w = 5.9	15.0	in [18]
1999 Kocaeli, Turkey earthquake	M_w = 7.4	16.0	in [18]
2001 Gujarat, India earthquake	M_w = 7.7	16.0	earthquakes.usgs.gov
2003 Bam, Iran earthquake	M_w = 6.6	15.0	earthquakes.usgs.gov
2005 Kashmir, Pakistan earthquake	M_w = 7.6	15.0	earthquakes.usgs.gov
2008 Wenchuan, China earthquake	M_s = 8.0	14.0	in [18]
2010 Baja California Norte, Mexico earthquake	M_w = 7.2	4.0	earthquakes.usgs.gov
2010 Port-au-Prince, Haiti earthquake	M_w = 7.0	13.0	earthquakes.usgs.gov
2010 Offshore Concepcion, Chile earthquake	M_w = 8.8	22.9	earthquakes.usgs.gov
2010 Christchurch, New Zealand earthquake	M_w = 7.0	12.0	earthquakes.usgs.gov
2011 Eastern Turkey earthquake	M_w = 7.1	18.0	earthquakes.usgs.gov
2011 Offshore Honshu, Japan earthquake	M_w = 9.0	29.0	earthquakes.usgs.gov
2013 Linqiong, China earthquake	M_w = 6.5	14.0	earthquakes.usgs.gov
2013 Bandar Bushehr, Iran earthquake	M_w = 6.4	12.0	earthquakes.usgs.gov
2014 Iquique, Chile earthquake	M_w = 8.2	25.0	earthquakes.usgs.gov
2015 East of Kudi, Nepal earthquake	M_w = 7.8	8.2	in [18]
2017 Iran-Iraq earthquake	M_w = 7.3	19.0	earthquakes.usgs.gov
2016 Central Italy earthquake sequence	M_w = 6.1, 5.9, 6.5		[33]
2019 Albania earthquake	M_w = 6.4	20.0	earthquakes.usgs.gov
2020 Aegean Sea earthquake	M_w = 6.9	21.0	earthquakes.usgs.gov
2021 Haiti earthquake	M_w = 7.2	10.0	earthquakes.usgs.gov
2022 Afghanistan earthquake	M_w = 6.2	4.0	earthquakes.usgs.gov

3. Archaeoseismology

Following Hinzen [6], archaeoseismology, also known as earthquake archaeology, is a subdiscipline of seismology that investigates pre-instrumental earthquakes that, by affecting sites of human occupation and their surroundings, have left their physical mark in ancient manufactured structures unearthed by archaeological excavations or on the monumental cultural heritage. These physical marks, relevant for archaeoseismic research, are occasionally (i) displacements along shear planes directly linked to the earthquake fault plane or its branches; (ii) off-fault-shaking effects including fractured building elements, tilted walls, a shift of building elements, lateral distorting, braking and overthrow of walls, rotations of vertically oriented objects; (iii) the secondary shaking effect's lateral spreading, mass wasting and cyclic mobility as a consequence of soil liquefaction; and (iv) archaeologically detected abandonment of a site and evidence of repair and rebuilding.

Archaeoseismology brings together the efforts of seismologists, archaeologists, earthquake engineers, civil engineers, geologists, geoarchaeologists, architects and historians [53,54] towards the assessment of archaeoseismic evidence, the expansion of both the pre-instrumental and instrumental earthquake catalog and the assessment of the seismic hazard of a region [45,55,56]. Specific questions investigated by archaeoseismology are (i) how probable are seismic ground motions, or secondary earthquake effects, as the cause of damage observed in anthropogenic structures from the past; (ii) when did the damaging ground motion occur and (iii) what can be deduced about the nature of the causing earthquake [7].

Figure 3 shows examples of structural damage documented in various archaeological sites worldwide. Sometimes, several of these seismogenic marks are found in one or various chronologically stacked destruction horizons, so-called earthquake strata, a term introduced by British archaeologist Sir Arthur Evans in the 1920s [57]. The phrases' earthquake-indicators' [58], 'destruction' layers [59] and 'earthquake-horizon' [60] are surrogates of the term earthquake stratum. Although the archaeological community widely uses the term earthquake stratum, they seem not to have established a systematic methodology for identifying and appraising archaeoseismic damage to manufactured objects [61]. Archaeological (i.e., coins, inscriptions, characteristic objects and pottery) and historical material generally can assist in dating possible seismic events [56,62,63].

Archaeoseismology utilizes data and techniques different from conventional seismology and earthquake geology, which rely on instrumental and historical records and structural data [56]. It is challenging to determine the precise cause of structural damage in archaeological records since various natural causes might yield similar-looking damage patterns and anthropogenic action can also create similar damage or permanent deformation [64,65]. Nonetheless, established qualitative archaeoseismic criteria have helped to distinguish seismic-induced structural damage to ancient structures from other natural and anthropogenic causes [6–8,45,56,58,59,61,66–68].

Nowadays, archaeological excavation-parallel [53,65,69] or non-excavation [48,70,71] three-dimensional (3D) laser scans of damaged archaeological structures accompanied by a quantitative damage analysis allow a fast and accurate identification, classification, quantification and testing of structural damage at a site and can assist archaeological work during or after archaeological excavation. Moreover, the 3D surface meshes derived from the same scan data can become the basis for developing virtual discrete element models of large and small anthropogenic structures of archaeological context such as rooms, aqueducts, wells, walls, terracotta vessels and figures [8,48,53,69–73]. The available discrete element models can then be used to test their stability using input ground motion signals (i.e., analytical, simulated earthquakes (assumed or historically documented), instrumental earthquakes, or strong motion records) to see if the structures topple or collapse [74], hence, allowing the determination of maximum upper ground motion bounds. Even the reconstruction of the slip velocities during ancient earthquakes based on faulted archaeological structures is now possible (i.e., [75]).

Archaeoseismic investigations have evolved from a qualitative (i.e., [56,59,66,76–83]) to a quantitative approach (i.e., [6–8,23,40,44–48,50–52,69,73–75,84]). The qualitative approach examines the typology of earthquake effects on architectural remains [66], sometimes including the landscape surrounding the site [78]. This kind of approach presents advantages and disadvantages. For instance, the criterion of Stiros [66] identifies earthquake-related structural damage to anthropogenic structures strictly from archaeological data, providing the elimination of natural and anthropogenic causes; however, the technique leaves various unanswered cases of destruction of architecture and abandonment of the site and it does not account for the effects of co-seismic morphological changes to the ground surface. For instance, the criterion of Rodriguez-Pascua et al. [78] utilizes the ground surface's observed 'seismic deformation pattern' and the toppled patterns of archaeological artifacts to construct a theoretical strain ellipsoid for the archaeological site under investigation. However, it does not determine the source parameters of the causative fault. The significant assumptions are that the observed toppled pattern(s) is co-seismic and that the resulting surficial expression of the morphogenic fault has remained unaltered. Then, the systematically derived theoretical strain ellipsoid is compared with the historical-to-present tectonic stress field pattern, active faults, or nearby active seismic zones to gain a deeper insight into the potential earthquake source(s).

Figure 3. Examples of deformations and damage which are possibly earthquake effects: (**A**) the horizontally deformed wall of a crusader fortress built on top of the Dead Sea Transform Fault in the Jordan Valley; (**B**) the deformed vault of a Roman sewer in Cologne, Germany; (**C**) toppled columns of a Byzantine church in Sussita located above the Sea of Galilee; (**D**) toppled column of the great palace in Petra, Jordan; (**E**) moved block in an arch of the Nimrod fortress in the Golan Heights; (**F**) shifted blocks of an analemma of a Roman theatre in Pınara, SW Turkey; (**G**) moved blocks of a corner wall of a Roman monument in Patara, SW Turkey; (**H**) shifted blocks of a Roman grave house in Pınara, SW Turkey; (**I**) spall of block corners, same object as in (**G**); (**J**) broken and horizontally displaced fortification wall of the Roman Tolbiacum (Zülpich, Germany); (**K**) rotated Lycian sarcophagus in Pınara, SW Turkey. (Photos courtesy of K.G. Hinzen).

Conversely, quantitative archaeoseismic studies of toppled columns strongly suggest that it is not straightforward to deduce a reliable back azimuth toward the earthquake source based on the deformation and toppled patterns of manufactured structures [72,85]. Therefore, it is impossible to establish a direct link between the orientation of a fallen object and the tectonic stress field of a past earthquake. The method of Rodriguez-Pascua et al. [78] has somewhat limited quantitative applicability, so conclusive interpretations from their approach should be considered cautiously. Buck [61] provides a literature review and thoroughly examines the several qualitative methodologies adopted to appraise archaeoseismic damage. She concludes that, when using the universal identification criteria (e.g., 'check-list' approach), interpretations of qualitative observations are commonly subjective and lack the site's human and physical context. Therefore, she proposes a project-specific interdisciplinary approach to assess archaeoseismic damage objectively.

Moreover, the systematically designed quantitative archaeoseismic approaches of Galadini et al. [6] and Hinzen et al. [8] test 'archaeoseismic evidence' before considering it reliable for quantitative comparison against the observed damage structures. These methods propose an analytical/numerical modeling procedure for archaeoseismic projects. The approach builds upon available upfront and newly collected geotechnical, geological, geophysical, geoarchaeological, archaeological and historical data. In most cases, newly collected field or laboratory data (e.g., geological, geophysical and geotechnical) is tailored to answer specific archaeoseismic questions [7]. Following the quantitative procedure, an archaeoseismic project is likely to become unique (cf. [61]). An up-to-date summary of archaeoseismological studies using advanced measuring methods and quantitative numerical modeling is given by Hinzen et al. [8]. Galadini et al. [6] discuss the methodologies and procedures in archaeoseismological research in detail.

4. Geological Site Effects in an Archaeoseismological Context

The primary objectives of a quantitative archaeoseismic investigation are to estimate the ground motion that caused the damage [8] and obtain information about the earthquake source that caused the ground motion [6]. Hinzen et al. [47] point out that archaeoseismic observations are often limited to a small portion of the meso-seismal area and uncertainties often hinder the correlation of damage across several neighboring sites in dating the damaging events [6,82]. These factors can strongly bias the estimation of the strength of ancient earthquakes; therefore, the consideration and systematic assessment of local seismic site effects become critical in an archaeoseismic study [47].

In principle, neglecting ground amplification in archaeoseismological studies might lead to an overestimation of the size of an ancient damaging earthquake [7]. For seismic ground motion simulations, the use of only one horizontal component as an earthquake input signal in site response analysis can lead to a significant underestimation of seismic site response [25] and the dynamic soil properties (e.g., density, shear wave velocity, damping) should (preferably) be measured in situ [86]. Hence, if the goal is to estimate local site effects in archaeoseismology, it is appropriate to implement some quantitative tools used in earthquake engineering (cf. [6]). The estimation of surface ground motion can be carried out empirically with records of actual earthquakes (cf. [47]) or numerically with the stochastic or Green's function methods [48,49,87]. Field tests and analytical/numerical models can assess the characteristics of seismic site amplification [23,47,88], recording and analyzing sites' dynamic responses using active sources, ambient noise and actual earthquakes.

Analytical/numerical models are convenient in quantitative archaeoseismology because they can develop an understanding of seismic wave propagation characteristics of sedimentary basins when instrumentally recorded earthquake records and macro-seismic intensity data from historical records are absent [35,40,43,89–91]. These models require a conceptualized geotechnical model containing the geometry of all soil layers from bedrock to surface, their dynamic properties, the incident bedrock motions and 'realistic' synthetic earthquake records mainly obtained from rock sites. Synthetic earthquake ground motions are calculated based on carefully selected earthquake source parameters (i.e., rupture length, rupture width, seismic moment (M_o) and moment magnitude (M_w)) linked to a seismotectonic model representative of the region of interest. Posteriorly, these synthetic ground motions are used as the earthquake input signal to calculate site amplifications and the resulting site-specific surface ground motion.

The environmental connection between the archaeological site(s) and its surrounding landscape must be recognized, mainly relying on archaeological, historical and geological insights. The relationship between isolated hard-rock ridges (i.e., outcropping bedrock) bordered by cohesive or granular soils (alluvium) is a condition frequently met for the design and construction of ancient architecture. Typically, archaeological sites were constructed directly on soft soils or exposed bedrock. Therefore, archaeoseismic research must establish the type of geology of the archaeological site of interest. For instance, archaeological excavation data may indicate a settlement developed on the sediments/soils deposited on hard bedrock, directly on hard bedrock, or ground conditions similar to a geomorphic scenario conceptualized in Figure 2.

5. Criteria for Forward Modeling Geological Site Effects in Archaeoseismology

From the seismic risk assessment point of view, an archaeological site within a seismically active region might be equivalent to a geotechnical site in a seismic region, even more so if the archaeological site records ancient structural damage to manmade structures. Generally, most archaeological sites worldwide occur in sedimentary basins or valleys; however, they also occur on topographic highs or slopes where topographic amplification can be an issue. The former observation is valid because most civilizations settled on accessible land with convenient environmental conditions that provided ecosystem services such as proximity to water, fertile arable land and canopy, among other natural features. A one-dimensional (1D) local site response (LSR) analysis is standard in geotechnical earthquake engineering. Its goal is to estimate the nonlinear cyclic response of soils subjected to earthquake-induced ground shaking, with either a nonlinear model or the equivalent linear model. A 1D LSR analysis can capture the essential aspects of surface ground response; however, it cannot model sloping, irregular ground surfaces, basin effects, topographic effects and embedded geologic structures, which are assessed adequately with 2D or 3D models. However, for most archaeological project aims and budgets, 2D or 3D modeling efforts are not cost-effective. Moreover, the 1D LSR analysis solves the problem of horizontally polarized vertically propagating shear waves with planar wavefronts from the bedrock into horizontally layered soils with frequency-independent damping (i.e., valley-like geology). The 1D LSR analysis considers the wave modification properties of layered, damped soil deposits overlying weathered or unweathered elastic bedrock.

Furthermore, following Zhang and Zhao [92], the use of 1D site models from sedimentary basins with a width-to-depth ratio (WDR) ≥ 6 is valid for a 1D LSR analysis. So for cases where the sedimentary basin's width is much greater than its thickness, the 1D LSR analysis is justifiable. In addition, it is cost-effective for archaeological projects' budgets.

The forward modeling of geological site effects through a 1D LSR analysis requires the proper knowledge of the site model parameters, including the conditions of the ancient ground surface and subsurface knowledge of the earth material properties (e.g., density, shear-wave velocity and seismic wave attenuation) and the computation of synthetic seismograms (i.e., surface acceleration time-series) using earthquake source parameters of hypothetical causative earthquake scenarios. However, the selected earthquake scenarios should fall under the seismotectonic context of the region under investigation. This information serves as input for the actual calculations of the site-specific 1D LSR analysis.

Figure 4 illustrates the proposed conceptualized workflow for the forward modeling of 1D seismic site effects in an archaeoseismological project [18]. This workflow is explained as follows. There are three significant elements to this workflow: (1) the contextualization of the seismological models, which must obey the active tectonic scenario proximal to the archaeological site under investigation; (2) the development of multiple site-specific 1D geotechnical models within the archaeological site or complex; and (3) the actual computational tasks that generate synthetic acceleration time-series from hypothetical earthquake scenarios and the 1D LSR analyses of the selected 1D geotechnical site models.

5.1. Seismotectonic Model

In archaeology, written records of ancient earthquakes devastating manmade structures are scarce to non-existent (cf. [52]). Therefore, we must hypothesize about the possible earthquake scenario that might be a causative earthquake and can explain the destruction patterns documented by archaeological field observations. This step requires insights from earthquake seismology, tectonics and geology to gather information. See the upper-left panel in Figure 4. In this step, several earthquake scenarios must be developed and each one must contain realistic earthquake source parameters describing the possible physical conditions of the hypothetical causative rupturing fault. Of course, the fault geometry and faulting mechanism must stem from local field observations. The earthquake source parameters include moment magnitude (Mw), seismic moment (Mo), earthquake stress-drop (Δσ), surface rupture length (SRL), fault's structural data (i.e., strike, dip and rake), hypocenter depth, rupture velocity and the reference depth (to fault's upper edge. Values for these source parameters are found in a thorough literature search and are investigated and assigned by a seismologist. The source parameters become the input parameters to calculate synthetic earthquake-induced ground acceleration seismograms for reference sites, which excite the site-specific 1D geotechnical models (Section 5.2).

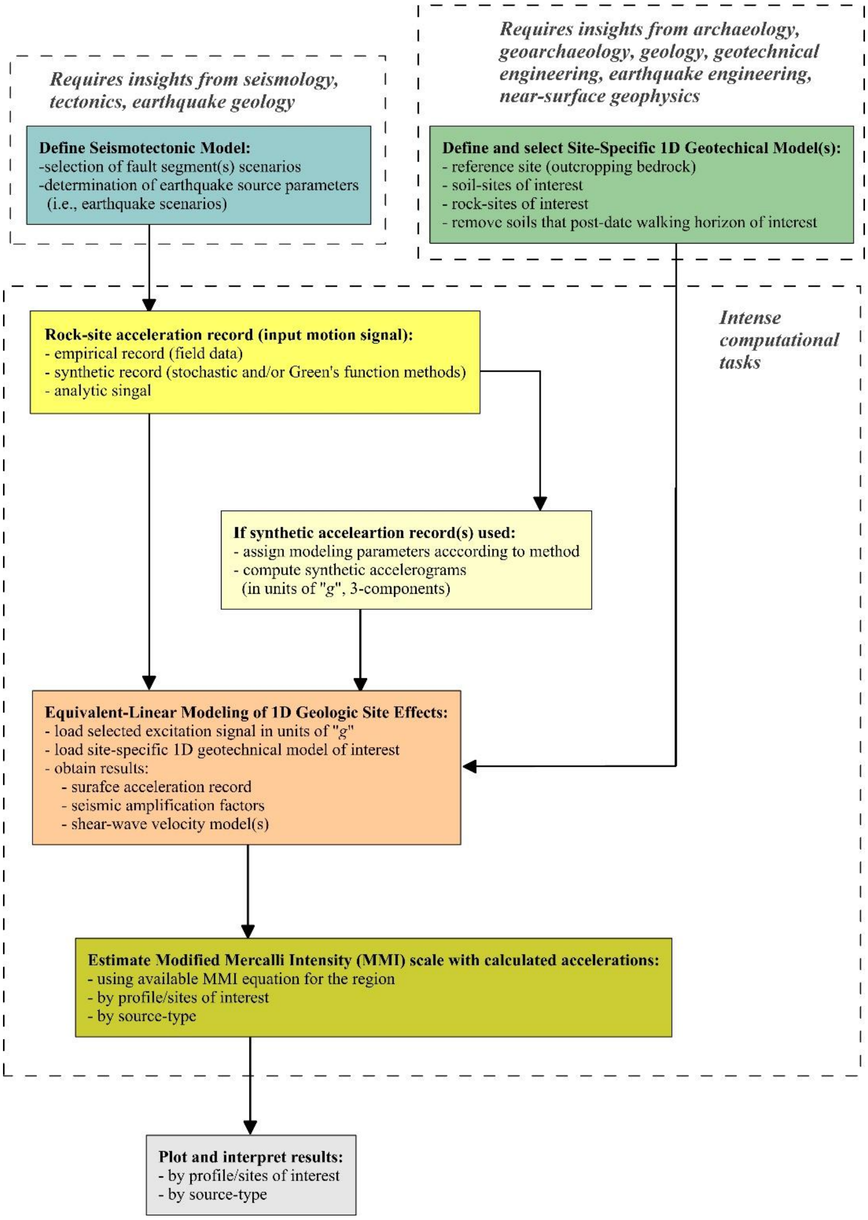

Figure 4. Schematized workflow of the proposed forward modeling of synthetic seismograms and 1D seismic site effects for an archaeoseismic project. The workflow honors an ancient earthquake's archaeological, geological and seismotectonic context. Modified with permission from [39]. Copyright 2016, Hinojosa-Prieto, H.R.

5.2. Site-Specific 1D Soil Models

When testing the plausibility of earthquake-induced destructions of an archaeological site, the evaluation becomes a geotechnical earthquake engineering problem. Therefore, retrospective site-specific 1D soil models must be developed for multiple locations throughout the archaeological site or complex. This step requires insights from archaeology, geoarchaeology, geology, geotechnical earthquake engineering and near-surface geophysics, as shown in the upper-right panel of Figure 4, so this step gathers information about the site's subsurface conditions.

Archaeological and geoarchaeological excavations, geophysical surveys and geological and geotechnical studies from the study area provide essential site-specific information required to estimate the geological site effects and define a site's seismic response. Archaeological and geoarchaeological excavations provide information about the texture, density, type, age and thickness of the shallow soils and sediments that pre- and postdate the stratigraphic horizon of interest; however, these excavations rarely reach the soil–bedrock interface. The removal of the overburden (i.e., material that postdates the horizon of interest) and the depth to the soil–bedrock interface are required for a realistic and accurate estimation of geological site effects. Without deeper boreholes and geophysical surveys, these should be pursued to detect the soil–bedrock contact and gain information about possible soil and bedrock heterogeneities. In general, seismic methods (reflection or refraction) provide an in situ measurement of the P and S wave velocities, while geoelectrical and electromagnetic methods can detect and discriminate between fine-grained soils (cohesive) from coarse-grained soils (granular).

Inaccurate knowledge of the actual composition, thickness and dynamic properties of the subsurface materials can lead to the misrepresentation of the site and the inaccurate selection of strain-dependent shear modulus and damping values for individual material layers and uncertainties in the forward calculation of frequency-dependent surface amplifications, surface ground-motions and the estimation of the seismic site response (cf. [93]). The site class definition is essential for seismic site-specific response analysis. The geotechnical site classification scheme of Rodríguez-Marek et al. [93] is the most adequate for archaeoseismic research because it allows an accurate stratigraphic representation of the regolith column compared to the geologic and geophysical site classification schemes. Therefore, the dynamic response of ancient anthropogenic structures is estimated with better accuracy. The geotechnical site classification system is based on several observable parameters: the type of deposit (i.e., hard rock, competent rock, weathered rock, stiff soil, soft soil and potentially liquefiable sand), which automatically introduces a measure of the dynamic stiffness (V_{s30}) to the classification system; depth to bedrock defined by $V_{s30} > 760$ m/s or to a significant seismic impedance contrast between surficial soil deposits and geologic material with a $V_s \approx 760$ m/s; the depositional age of the soil(s) (i.e., Holocene or Pleistocene); and soil-type (i.e., cohesive or granular). The geotechnical site classification system breaks down sites traditionally grouped as "rock" into competent rock sites and weathered soft-rock/shallow stiff soil sites. This subdivision significantly reduces uncertainty in defining site-dependent surface ground motions and allows more accurate determination of proper model parameters and dynamic properties to individual material layers.

Conversely, the geologic site classification scheme is based on one or more parameters obtained from surficial geologic observations, namely geologic age-only, age-and-depositional environment, or age-and-sediment texture [94]. This classification system does not provide information about the bedrock's depth and stiffness, a discriminating factor for a seismic site response analysis [93].

Moreover, the geophysical site classification scheme is based solely on the uppermost 30 m of the surface, V_{s30} [95]. The use of the V_{s30} has the advantage of uniformity within the 30 m depth range and correlates well with detailed surface geology (i.e., age-and-soil texture and age-and-weathering/fracture spacing for rock) [96,97]; however, it is still an oversimplification of most natural site conditions and, therefore, an indirect approach to define the actual composition and stratigraphy of the near-surface materials and to estimate the soil–bedrock interface.

5.3. Computational Tasks: Forward Modeling of Synthetic Seismograms and 1D LSR

This stage deals with the computation of synthetic acceleration seismograms of the reference site and the site-specific 1D LSR analysis. The synthetic seismograms from hypothetical earthquake scenarios are used as input signals in the 1D LSR analysis. The 1D LSR analysis deals with the ground surface's dynamic loading during the earthquake's duration. Each site-specific 1D LSR analysis yields a surface acceleration record and a seismic amplification factor. See the middle panel in Figure 4. In addition, when a ground-acceleration-dependent empirical relation of the Modified Mercalli Intensity (MMI) scale is available for the region, the computed site-specific ground accelerations that account for the geological site effects can be converted into an MMI value, as shown in the bottom of the middle panel of Figure 4. Hence, the computed surface ground motions, seismic amplification factors and MMI account for the geological site effects' assessment.

The choice of computer codes to calculate synthetic seismograms and to forward model the equivalent-linear 1D site response is also essential, tasks that a seismologist or geotechnical earthquake engineer should perform. Nowadays, high-frequency synthetic seismograms are computed for modeling geological site effects [98,99]. Most high-frequency motions might be caused by direct P and S waves [100]. For modeling purposes, the computed synthetic seismogram should contain such body waves. However, not all algorithms can compute synthetic seismograms with distinct body waves, surface waves and high-frequencies (e.g., [101]). Nevertheless, the synthetic seismogram should be computed with an algorithm that allows the computation of high-frequency synthetic seismograms (i.e., near-field motions) with recognizable body and surface waves (e.g., [99]).

Several computer codes can model the nonlinear–elastic stress-strain behavior of a realistic 1D regolith column or geotechnical model [35,102–105]. The open-source code of Robinson et al. [104] used to forward the equivalent-linear 1D site-response model is an adequate code to forward model 1D local site effects in archaeoseismology. The code can incorporate uncertainties in the geotechnical model parameters, including density, shear-wave velocities and layer thickness. It also allows for defining thin material layers (<1 m thick), assigning strain-dependent shear modulus and degradation damping curves to each material layer and using either an average or a gradient shear-wave velocity model. While the shear-wave velocity of the subsurface materials within the archaeological site (e.g., 1D soil models) is measured in situ with near-surface seismic methods, the strain-dependent shear modulus (G/G_{max}) and damping ratio (ξ) degradation curves of the same materials can and should be tested in a laboratory. It is worth mentioning that these elastic parameters are noticeably different for rocks (sedimentary, igneous, or metamorphic) and soft sediments or soils (clay, sand, gravel); hence it is crucial to understand the site's stratigraphy fully.

The shear-wave velocity of the material layers is a fundamental model parameter for an equivalent-linear 1D site-specific response analysis. The use of an average shear-wave velocity (i.e., model A) for each material layer is an acceptable approach in the absence of depth-dependent (gradient) shear-wave velocities (model B). Nevertheless, the implementation of model A and model B yield similar results: model A typically produces a slightly higher amplification peak at a slightly lower frequency value than model B. The use of model B should be the first choice if available information (geologic and seismic) shows an increase in geologic age, density, consolidation and shear strength with increasing depth. In this way, the stiffness of the near-surface materials would be accurately represented. Conversely, model A should be adopted when the presence of homogenous material layers is demonstrated by data from geologic logs and archaeological and geoarchaeological excavations or when a gradient velocity model cannot be constrained for the depth interval of interest.

Figure 5 provides an example of four individual simulations using the equivalent-linear model for two 1D site-specific cases from a Late Bronze Age Greek archaeological site: a soil site (T1s1) and a rock site (T1s3). For one simulation, the input consists of one modeling site (e.g., T1s1 or T1s3) represented in two ways: by an average Vs-depth curve (model A) and a gradient Vs-depth curve (model B). Each case is accelerated with two synthetic accelerograms or input signals calculated using the Stochastic method (SM) and Green's function (GFM). The synthetic accelerograms correspond to a local strike-slip earthquake (M_w = 7.0). The output yields a computed site-specific surface acceleration record and a seismic amplification function for each case. This example shows how the soil site produces higher-surface acceleration and seismic amplification due to earthquake-induced ground motion compared to the adjacent stiffer rock site.

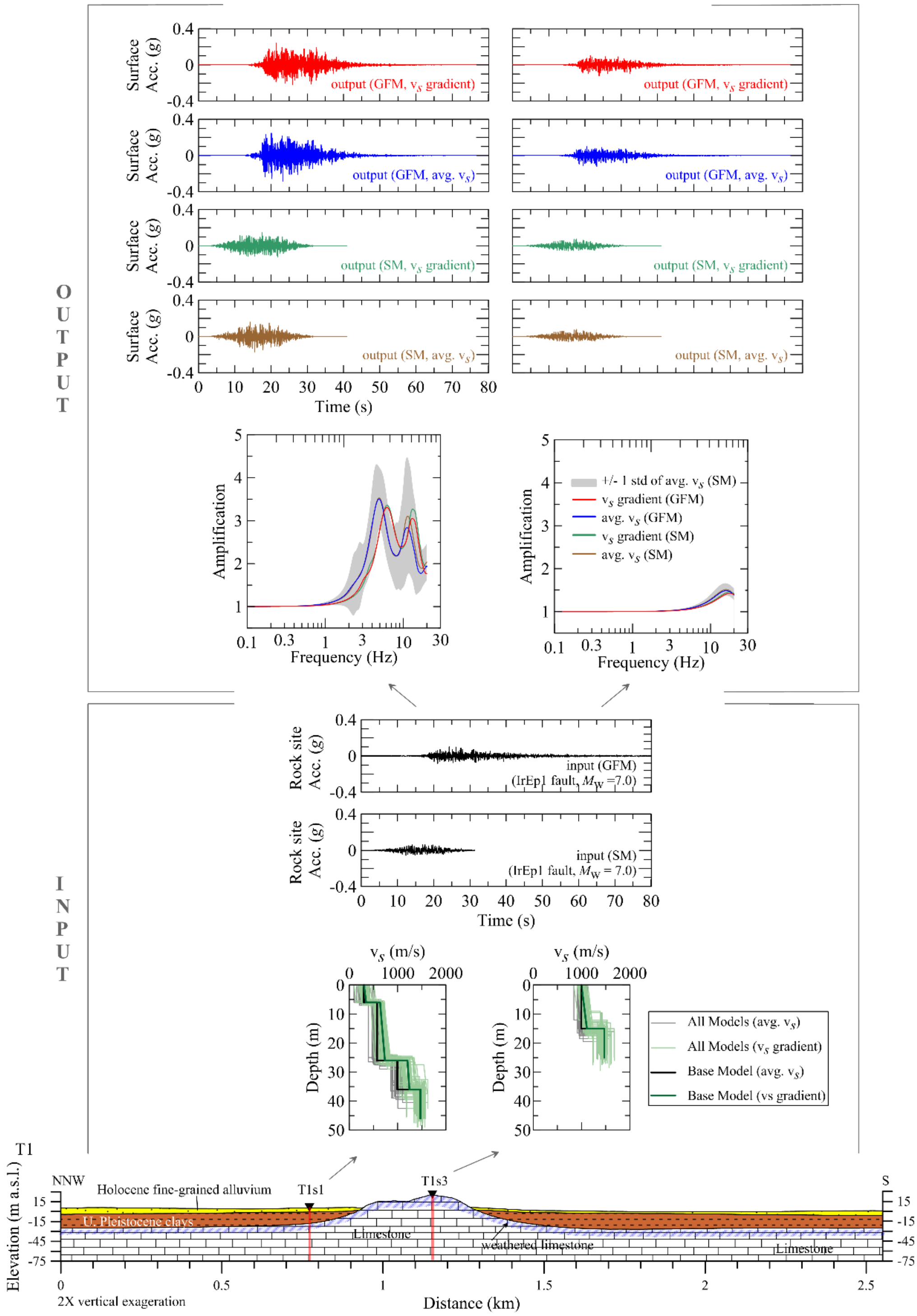

Figure 5. Example of four individual simulations using the Equivalent−Linear model for two 1D

site-specific cases from a Late Bronze Age Greek archaeological site (Tiryns): a soil−site (T1s1) and rock-site (T1s3) highlighted by the vertical red bars located along the geologic profile (**lower** panel). For one simulation, the input consists of one modeling site (e.g., T1s1 or T1s3) represented in two ways: by an average V_s model and a gradient V_s. Each case is accelerated with a synthetic accelerogram calculated with the Stochastic method (SM) and a synthetic accelerogram calculated with Green's function method (GFM) (**middle** panel). The synthetic accelerograms correspond to a local strike-slip earthquake (M_w = 7.0) triggered by the nearby Iria−Epidaurus fault segment. The output yields a computed site−specific surface acceleration record and a site−specific seismic amplification function (**upper** panel). Used with permission from [18]. Copyright 2016, Hinojosa−Prieto, H.R.

6. Discussion

During earthquakes, the ground surface undergoes multi-directional cyclic stresses with different frequencies and amplitudes leading to cyclic deformations and fluctuations in stress–strain and strength properties [18]. Near-surface materials typically comprise young, poorly to mildly unconsolidated soft soils deposited on stiffer consolidated sediments underlain by weathered to fresh bedrock, a stratigraphic column commonly referred to as regolith. Regolith can amplify surface ground motion during an earthquake [104,106]. Real surface ground-motion scenarios usually involve a heterogeneous sequence of soil deposits of varying textures, stiffness and damping characteristics with interfaces at which elastic wave energy is reflected and transmitted [16,18,93]. Seismic waves amplify due to the impedance contrast between hard-rock (bedrock) and the overlying sediments and soils [18,22,25]. A site with relatively softer soils over bedrock, typically referred to as a soil site, will amplify low-frequency (long-period) bedrock motions more than a nearby site with relatively stiffer soils over the same bedrock [18]. These last two amplification scenarios are expected to occur in Quaternary sedimentary basins because of the abundance of softer alluvial soils deposited around archaeological sites, of which stiffness changes up section due to their geologic age and heterogeneous textures.

Archaeologists often face the tempting decision of assigning ancient co-seismic structural damage due to past earthquake ground-shaking to archaeologically documented destroyed constructions. Assessing the geological site effects of an ancient earthquake is more or less similar to assessing it in a contemporary (instrumental) or future earthquake scenario because well-accepted modern earthquake engineering techniques are applied to solve the same problem. However, uncertainty might stem from the calculated synthetic seismograms despite relying on carefully selected and vindicated input parameters found in the literature or modeled, a common challenge in numerical simulations of surface ground motions, particularly for reconstructed ancient earthquake scenarios. Radiometrically dated and geo-physically constrained exposed geological fault scarps offer incredible insights that enhance the selection process of a causative fault or earthquake.

Generally, the soils around an archaeological zone are young and soft, while any buried or exposed bedrock is often older, stiffer and more resistant to earthquake-induced ground shaking. From an anthropological and archaeological perspective, while modest ancient manmade constructions were constructed in soils, more resistant and massive fortified constructions were built on shallowly buried or exposed bedrock. From the civil and earthquake engineering point of view, soil sites can undergo higher levels of seismic amplification and surface ground-shaking and record higher earthquake intensity, likely leading to an observable town-wide devastation pattern in archaeological zones than bedrock sites.

Because of the geological site effects, earthquakes do not need to be of considerable magnitude and have a short epicentral distance to instigate structural damage to anthropogenic constructions. A moderate-to-strong earthquake-induced ground motion influenced by geological site effects and a long epicentral distance can cause significant structural damage (i.e., the 1985 Michoacán Mexico earthquake). Therefore, in archaeoseismology, a local site response analysis can quantitatively estimate the possible levels of ancient ground acceleration, seismic amplification and ultimately the MMI value, resulting in the identification of areas with higher potential of ground motion from which isoseismal lines can be computed and drawn, leading to a more accurate reconstruction of a macro-seismic intensity map. Hence, neglecting the role of geological site effects in archaeology and archaeoseismological research might lead to an underestimated or overestimated size of the ancient earthquake and inaccurate estimates of surface ground motions, seismic amplification factors, macro-seismic intensities and, ultimately, seismic hazard assessments. The seismic hazard assessment is of paramount importance for risk estimation.

The 1D LSR analysis allows the calculation of site-specific seismic amplification and associated surface ground motions at multiple sites due to potential ancient earthquake ground shaking. If ground-acceleration-dependent empirical relations of MMI are available for the region of interest, the site-specific MMI value can be calculated using the computed surface accelerations obtained in the 1D LSR analysis. Hence, if a distribution of MMI values is obtained, isoseismal lines can be drawn for the study area leading to a more accurate reconstruction of a macro-seismic intensity map that considers the geological site effects. From such comprehensive 1D LSR and synthetic earthquake scenarios, one can shed light on the possible causative earthquake that might explain the archaeologically-documented physical damage to anthropogenic structures.

7. Conclusions

Knowledge of the locations of ancient earthquakes is essential in studies of earthquake forecasting, strong ground motions, seismic hazards and seismo-tectonics [107,108]. Unfortunately, estimating the epicenter of an ancient earthquake is usually charged with uncertainties, which arise due to difficulties in interpreting many historical accounts, destruction layers, spatial inhomogeneities of the locations from which the available accounts come, biases due to geological site effects and other issues [107]. For decades, archaeologically estimated macro-seismic intensity (e.g., MMI) has been a proxy to back-calculate the strength and location of ancient earthquakes (e.g., [52,59,83,107–109]), but often lacking the contribution of the geologic and topographic site effects, hence providing limited cues about the level of surface ground-motions and the meso-seismal area. In studying ancient earthquakes, it is essential not to rely solely on estimated earthquake intensities and meso-seismal area derived from qualitative archaeological excavation data and descriptive field annotations to estimate the size and strength of a causative ancient earthquake, because this might introduce unrealistic earthquakes to the earthquake catalog of the region under investigation, leading to an inaccurate seismic hazard assessment.

Moreover, it is clear that seismograms (e.g., acceleration time series) of ancient earthquakes pre-dating the instrumental period do not exist in an archaeoseismic project; thus, co-seismically damaged anthropogenic structures function as seismoscopes, which are the closest to a seismogram. Henceforth, in archaeoseismology, the absence of a surface acceleration time series impedes the direct estimation of earthquake source parameters and other observables, so only using numerical models to calculate synthetic seismograms with the role of geological site effects is the only means to gain insights into the possible past surface ground motion, seismic amplification, macro-seismic intensity scenarios and the nature of the causative ancient earthquake.

The quantitative evaluation of geological site effects in archaeoseismology emerges as a multidisciplinary approach. Hence, the idea of seismically induced destruction of one of more ancient manmade structures (e.g., an earthquake hypothesis) can now be quantitatively verified via forward numerical modeling of the postulated causative fault's source parameters and its possible geological site effects. The term geologic site effects is sometimes replaced with seismic site effects, for instance, when seismic amplification factors, surface ground motions and corresponding earthquake intensities have been estimated for any number of sites within an archaeological zone using forward numerical modeling scenarios.

A retrospective geotechnical site micro-zonation coupled with the calculation of surface ground motions, seismic amplification factors and earthquake intensity account for the geological site effects assessment. When forward numerical modeling of the probable causative ancient earthquake and related geological site effects refutes an earthquake hypothesis's plausibility, other explanations must be pursued to clarify the observed and interpreted destruction pattern in a given archaeological site. Conversely, suppose the results of the numerical simulations support the earthquake hypothesis. In that case, the hypothetical earthquake scenario(s), with the geological site effect contributions, may be added to the region's pre-instrumental and instrumental earthquake catalog under investigation, leading to an updating of the seismic hazard setting of the region.

The geological site effects must be considered when archaeological excavations discover, describe and interpret destruction layers, mainly when the aim is to develop an MMI catalog within the site or region under investigation. Conversely, seismic hazard risk assessments must pay close attention to archaeological reports describing plausible evidence of past earthquakes lacking the consideration of geological site effects.

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