Topography Effects in the 1999 Athens Earthquake: 
Engineering Issues in Seismology

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Abstract—During the 1999 Athens Earthquake, the town of Adàmes, located on the eastern side of the Kifissos river canyon, experienced unexpectedly heavy damage. Despite the significant amplification potential of the slope geometry, topography effects cannot alone explain the uneven damage distribution within a 300m zone behind the crest, characterized by a rather uniform structural quality. This paper illustrates the important role of soil stratigraphy, material heterogeneity and soil-structure interaction on the formulation of surface ground motion. For this purpose, we first perform elastic two-dimensional wave propagation analyses based on available local geotechnical and seismological data, and validate our results by comparison with aftershock recordings. Next, we conduct inelastic time-domain simulations that include spatial variability of soil properties and soil-structure interaction effects, to reveal their additive contribution in the topographic motion aggravation.

Keywords—Site effects, topography, stratigraphy, 2D wave propagation, inelastic soil behavior, random properties, soil-structure interaction

INTRODUCTION

It has been long recognized that topography can significantly affect the amplitude and frequency characteristics of ground motion during seismic events. In the recent past, documented observations from destructive seismic events show that buildings located at the tops of hills, ridges and canyons, suffer more intensive damage than those located at the base: the Lambesc Earthquake [France 1909], the San Fernando Earthquake [1971], the Friuli Earthquake, [Italy 1976], the Irpinia Earthquake [Italy, 1980], the Chile Earthquake [1985], the Whittier Narrows Earthquake [1987], the “Eje-Cafetero” Earthquake [Colombia, 1998] and recent earthquakes in Greece [Kozani, 1995 and Athens, 1999] and Turkey [Bingöl, 2003] are only some examples of catastrophic events, during which severe structural damage has been reported on hilltops or close to steep slopes.

Still nowadays, topographic amplification is poorly understood and the insufficient number of documented evidence prevents these effects from being incorporated in most seismic code provisions and microzonation studies, despite their undisputable significance in engineering practice. Instrumental studies that have been performed in recent years verify the macroseismic observations, by predicting systematic amplification of seismic motion over convex topographies such as hills and ridges, de-amplification over concave topographic features such as canyons and hill toes, and complex amplification and de-amplification patterns on hill slopes. The problem of scattering and diffraction of seismic waves by topographical irregularities has been also studied by many authors. The majority of these studies focus on two-dimensional simulations in which the topographic asperities are treated as isolated ridges or depressions, usually on the surface of homogeneous elastic media. Comparison between instrumental and theoretical results reveals that there is indeed qualitative agreement between theory and observations on topography effects. Nevertheless, from a quantitative viewpoint, there still exists clear discrepancy in numerous cases, where the observed amplifications are significantly larger than the theoretical predictions. Furthermore, results from instrumental studies on weak motion data or ambient noise may not be applicable to describe topography effects for strong ground shaking, which is usually associated with inelastic soil response. Indeed, there exist very few—if any—well documented case studies where topography effects are illustrated for strong ground motion.

This paper uses a case-study from the Athens 1999 earthquake to illustrate the decisive role of local stratigraphy, material heterogeneity and soil-structure interaction in altering the energy focusing mechanism at the vertex of convex topographies. The effects of local soil conditions are validated by comparison with weak motion data. The effects of inelastic soil behavior and nonlinear soil-structure interaction are then illustrated for the strong motion recordings. Our conclusions can be used as guideline for more rigorous analyses to be performed, accounting for the additive contribution of engineering issues in the extensively studied seismological problem of topographic motion amplification.

THE 7-SEPT-99 EARTHQUAKE

The M, 5.9 event that shook Athens just three weeks after the M, 7.4 Kocaeli Earthquake has been characterized as the worst natural disaster in the modern history of Greece. This moderate event had a major socio-economical impact, resulting in the loss of 150 lives, the collapse of 200 residential and industrial buildings and the severe damage of another 13,000. Despite the acquired knowledge after two-and-a-half millennia of history, no earthquake has ever been assigned to or near the 1999 seismogenic fault. The location of the ruptured fault and the geography of the heavily damaged region, are schematically illustrated in Fig. 1. Also shown on the same Figure are the locations of the four accelerograph stations, which recorded the strongest motions: KEDE, MNSA, SGMA and SPLB.
Adámes: Observations, Topography, Stratigraphy

One of the most heavily damaged areas was the small community of Adámes, located next to the deepest canyon of Kifissos river, the main river of the Athens metropolitan area. The majority of local buildings, constructed in the 70's and early 80's, comprise 2- to 4-storey concrete reinforced structures of rather uniform quality. Nevertheless, the MMI in the 1200m long and 300m wide town ranged from VIII to IX+, despite its 8-10km distance from the projection of the causative fault.

The location of the town next to the crest of the canyon in conjunction with the high damage intensity (as opposed to numerous other towns located at equal or smaller distances from the source where MMI did not exceed a mere VII) brought forward topography effects to justify the macroseismic observations. Behind the crest however, damage was bilaterally non-uniform, and in the parallel to the river axis direction, was concentrated in two zones: one next to the crest and one at a distance about 200m-300m from it. Some scattered -yet less intense- damage was observed at intermediate locations. It seems therefore, that focusing of seismic energy at the vertex certainly played a significant role but was not the only phenomenon involved.

A topographic survey of the canyon produced the cross-section shown in Fig. 2. The slightly idealized geometry of the canyon used in our investigation is also shown in this figure. Note the 40m deep and the nearly 2:1 (horizontal to vertical) slope of the canyon cliff.

Geotechnical investigations of the area comprised the drilling of ten (10) boreholes with Standard Penetration Blow Count (N\text{SPT}) measurements and laboratory testing for the definition of the variation of plasticity index ($I_p$) with depth. Eight of these were performed down to a depth of about 35 m, and two reached almost 80 m. Some indirect evidence for greater depths was “extrapolated” from two 150-m-deep boreholes drilled for the under-construction Olympic Village, 1.5 km west to northwest of Adámes. The overall picture emerging from this investigation is shown in Fig. 3, where low-strain shear wave velocity profiles are constructed for three characteristic locations in Adámes, referred to in the ensuing as profiles A, B and C. All profiles comprise alternating soil layers of silty-gravely sands and sandy-gravely clays in the top 20-30m. The approximate average velocity, $V_{S30}$ of the 30m surface soil layers for the three profiles are: 500 m/sec for profile A, 400 m/sec for profile B and 340 m/sec for profile C, indicative of very stiff (profile A), just stiff (profile B), and moderately stiff (profile C) soil formations according to the European Seismic Code (EC8).

**Fig. 2:** Typical cross-section of the topographic relief of Kifissos river canyon and the region of Adámes

**Fig. 3:** Shear wave velocity variation with depth of three characteristic soil profiles in Adámes

**Strong Motion Records**

Fifteen strong-motion accelerograph stations were triggered by the main shock within 25 km from the causative fault, recording peak ground accelerations (PGA) ranging from about 0.05 g up to 0.50 g. Their location is depicted in Fig. 1. Nevertheless, there were no records in the meizoseismal area. Due to lack of acceleration records in the area of interest, these strong motion time-histories were used in our simulations. To recover the corresponding motion at rock-outcropping, numerical 1D or 2D deconvolution analyses were performed for the recordings obtained at stations where local soil conditions or adjacent structures have altered the bedrock input motion.

Nevertheless these motions were recorded within a narrow region located 10 km away from the end of the ruptured zone, in a direction perpendicular to it, whilst -by contrast- the Kifissos river canyon lies in front of the rupture zone. There is, therefore, strong indication that forward rupture directivity is likely to have affected the ground motion in the town of Adámes. Accounting for near fault effects implies the selection of appropriate time histories characterized by a relatively simple long period pulse of
strong motion having relatively short duration, which cannot
be described by a relatively long stochastic process, as is
indeed the case in more distant seismic events. Two historic
time-histories have been identified in the world strong-
motion database from the 1966 M= 5.6 Parkfield, CA
Earthquake, which encompass such long-period character-
ristics, recorded at the Cholame Shandon No. 8 and Temblor
stations.

The response spectra of these six acceleration time
histories, which represent the general strong motion
characteristics of the Athens event and possible directivity
effects anticipated at the area of interest, are plotted in Fig. 4.

For further details on the seismo-tectonics of the event,
the geotechnical investigation in Adàmes and the strong
motion data-processing, the reader is referred to Ref. [1], [2]
and [3].

Fig. 4: Acceleration response spectra of strong-motion recordings,
defined at rock-outcropping in our simulations

ELASTIC SIMULATIONS

We here investigate the diffraction potential of the slope
geometry, the frequency-dependence of topographic
amplification and the role of soil layering and material
heterogeneity by means of elastic finite-element parametric
simulations. Successively, the local site conditions are
modeled and our results are validated by comparison with
aftershock recordings.

Geometry: Fig. 5 illustrates the wavefield generated
by a cliff with the geometry of the Kifissos canyon, at the
surface of a homogeneous halfspace upon the incidence of
vertically propagating SV-waves. We here use a narrow-
band input, namely Ricker wavelet with normalized
frequency \( \omega_0 = 2 f_0 h / V_s = 1.00 \), where \( f_0 \) is the
central frequency of the pulse, \( h \) is the height of the cliff and \( V_s \)
the shear wave velocity of the halfspace. The Poisson’s
ratio of the elastic medium is \( \nu = 0.35 \), typical of stiff clayey soils.

The direct / diffracted wavefield shown in Fig. 5
comprises the following waveforms: (i) Direct SV waves
(denoted SV), (ii) forward scattered Rayleigh waves
(denoted R1) generated at the boundaries of the shadow /
illuminated zone at the lower corner of the cliff, propagating
along the cliff and being forced to change direction at the
upper corner, (iii) Backward scattered Rayleigh waves
(denoted R2) generated at the boundaries of the shadow /
illuminated zone at the lower corner of the cliff and
propagating outwards, and (iv) surface waves (denoted SP)
that are generated along the cliff and propagate upwards
approximately with the P-wave velocity. As a result of this,
they arrive in the vicinity of the crest almost simultaneously
with the direct SV-wave.

The significant enhancement of forward scattered
Rayleigh waves (resembling forward directivity effects),
along with the presence of surface waves traveling along the
slope with velocity of propagation which approaches the P-
wave velocity can be explained from the combination of the
slope angle and material Poisson’s ratio corresponding to the
present analysis: for \( \nu = 0.35 \), critical incidence is calculated
as:

\[
\theta_{cr} = \arcsin \left( \frac{V_s}{V_p} \right) = 28.71 \approx i = 30
\]

Therefore, vertically propagating waves strike at the free
surface of the slope with almost critical incidence, resulting
in the transformation of practically all the incident energy
into surface waves that travel along the slope and
constructively interfere with the direct SV waves that arrive
behind the crest. Therefore, the site conditions in Adàmes
satisfy a priori conditions which favor a complicated and
detrimental diffraction potential, simply by considering the
elastic response of the canyon cliff.

Note also that despite the horizontally-polarized particle
motion of the incident seismic input (vertically propagating
SV waves), the surface response contains a parasitic vertical
acceleration component as well. This corresponds to the
vertical particle motion of surface diffracted waves, and is shown to carry significant portion of the seismic wave energy. For the illustrated case, its normalized amplitude is of the order of 35% of the peak surface acceleration at the far-field.

**Frequency of incident motion:** Fig. 6 illustrates the spatial distribution of peak surface acceleration (horizontal and vertical) behind the crest, for vertically incident SV Ricker wavelets with different central frequencies. The response is normalized by the peak acceleration at the far-field, defined here at distance 300 m from the vertex, where 2D phenomena are shown to be negligible.

![Graph](image)

Fig. 6: Normalized horizontal (top) and vertical (bottom) peak surface acceleration behind the crest (x = 300 m) as a function of the frequency content of the incident pulse.

The main conclusions drawn from our investigation are the following:

(i) The diffraction problem of topographic amplification is strongly frequency-dependent. The location of peak horizontal acceleration behind the cliff is controlled by the dominant wavelength (λd) of the incident motion (here the central frequency of the Ricker wavelet) and is systematically observed at a distance x = 0.2 λd from the crest (see also Ref. [4]). The amplitude of peak acceleration at this location is also frequency-dependent, and increases almost linearly with frequency.

(ii) The amplitude of the parasitic acceleration component is also frequency-dependent. For the high-frequency input pulse in these simulations, the peak vertical response is on the order of 60% of the corresponding far-field response. Since the location of peak vertical acceleration is also frequency-controlled, higher frequency components are amplified within a narrower zone in the vicinity of the crest.

(iii) The lobes of constructive and destructive interference at the surface -controlled by the frequency content of the incident waves- result in significant differential motion behind the crest and along the slope, where transition occurs between the convex and concave part of the topography.

Numerical simulations have also been performed for a homogeneous layer overlying elastic halfspace, for various impedance contrasts. Our results show that the bedrock-soil impedance ratio that controls the seismic energy trapped in the surface layer and the corresponding one-dimensional amplification of the motion, introduces additional complexity to the problem studied. Resonance of the shallow (in front of the toe) or deep (behind the crest) far-field soil columns not only controls the overall response of the configuration, but indeed enhances the topographic amplification of motion by altering the diffraction mechanism.

The frequency-dependence of the amplification mechanism can be summarized as follows: (i) for a constant input motion, topographic aggravation of the response increases with increasing height of the topographic feature (h), and (ii) for a given feature, topographic amplification increases with frequency, yet occurs within a more confined zone in the vicinity of the vertex (it is shown that max(ahor) occurs at x = 0.2λd and max(avs) at x = 0 m from the crest).

**Soil Layering:** The effect of soil layering is here examined by means of a single surface layer, of thickness h1/h = 0.25 and variable shear wave velocity (Vs1), overlaying homogeneous halfspace. Results are shown for a soft-surface layer with V1 / Vs = 0.5, where Vs is the shear wave velocity of the halfspace. This is indeed an idealized model for typical soil profiles in Adámães, but also for many sedimentary soil deposits.

Fig. 7 illustrates the effects of a surface soft layer on the normalized surface response, by comparison with the homogeneous halfspace ground motion. Results can be summarized as follows:

(i) The incident wave energy is trapped within the surface layer, and multiple reflections interact with the surface waves that originate from the lower corner of the slope and propagate uphill. The scattered wavefield at the surface comprises Rayleigh waves that are generated at the crest and travel with the Rayleigh wave velocity of the surface layer, Vρ1, and reflections of waves that travel along the layer-halfspace interface with the Rayleigh wave velocity of the later, Vρ.

(ii) For high-frequency incident waves, the peak normalized horizontal acceleration of the stratified medium is lower than the corresponding of the homogeneous halfspace. Note however that the absolute motion amplification is very significant in the soft surface layer case, a fact that illustrates the dominant role of the far-field stratigraphy on the amplification mechanism behind the crest.

(iii) The vertical acceleration component is remarkably enhanced. This effect is prominent for incident waves with wavelengths short enough to see the surface layer. In this case, the vertical acceleration is shown to attain amplitudes 25% larger than the corresponding response at the far-field.

(iv) In the frequency domain, the far-field/2D transfer function is very erratic for wavelengths comparable with the thickness of the surface layer, i.e. its resonant frequencies.
Material Heterogeneity: We next investigate the effects of material heterogeneity on the topographic amplification of seismic motion. For this purpose, we generate Gaussian shear wave velocity stochastic fields using a univariate spectral density function, namely the exponential decaying SDF (Eq. 1).

\[
\rho_i(\xi) = \cos \left( 2 \tan^{-1} \left( \frac{\xi}{\theta_i} \right) \right) \left[ 1 + \left( \frac{\xi}{\theta_i} \right)^2 \right]^{-1/2}
\]

where \(\rho_i\) is the correlation function in spatial direction \(i\) (horizontal or vertical), \(\xi\) is the separation distance and \(\theta_i\) the correlation distance in the \(i\)th direction. Separate correlation structures are assigned to the horizontal and vertical direction, which are functions of the correlation distance, and the correlation function of the stochastic field is defined as their product. The random fields are generated in the wavenumber domain and successively denormalized and mapped on deterministic finite element models. The effects of correlation distance of the simulated random media, relative to the propagating wavelengths, are then evaluated by means of Monte Carlo simulations (Ref. [5]).

Comparison of time and frequency-domain results with the corresponding response of a homogeneous halfspace with the same background stiffness, illustrates phenomenological scattering attenuation for long wavelengths and enhancement of frequency components whose wavelengths are comparable with the horizontal correlation distance of the random medium.

In particular, the spatial distribution of peak normalized surface acceleration is practically the same – or slightly lower – than the halfspace response, yet individual simulations show significant amplification of the vertical component and enhancement of the high-frequencies of the incident motion. In addition, multiple wave reflections at the localized material heterogeneities significantly increase the duration of the surface response. Fig. 8 illustrates the Fourier amplitude surface of the response behind the crest, for a typical realization of the stochastic field with \(\theta_z / \lambda_0 = 0.0625\) and \(\theta_x / \lambda_0 = 0.625\). Clearly, the erratic frequency content of the response and the amplification level of high frequency components cannot be simulated by means of a homogeneous medium.

Local Site Conditions and Recorded Field Evidence

The 2D response of the stratified soil configurations corresponding to profiles A, B and C is next evaluated by means of elastic simulations. The numerical model is now subjected to the strong motion time-histories described above, and results of our analyses can be summarized as follows:

(i) For the broad-band seismic input, topographic amplification occurs within a zone behind the crest, approximately equal to the width of the topographic irregularity (\(L = 70m\)). This is found to be in accordance with results of our parametric investigation.

(ii) Two-dimensional amplification of the horizontal response is shown to be rather insensitive to soil stratigraphy,
yet enhanced in comparison to the homogeneous halfspace case. Peak amplification is of the order of 0.30 $a_{ff}$, where $a_{ff}$ is the far-field peak surface acceleration. This is again consistent with amplification computed for $a_{q} \approx 4h/F_r$ in our parametric study, where $F_r$ is the mean shear wave velocity of the cliff profile.

(iii) The magnitude of parasitic acceleration however, shows strong dependence on the soil stratigraphy. This effect is primarily controlled by stiffness of the surface layer. In particular, results show that the amplitude of the vertical acceleration range from 0.25$a_{ff}$ for the stiffer profile A to 0.70$a_{ff}$ for the softer profile C, where $a_{ff}$ is the corresponding far-field peak surface acceleration.

Significant corroborations of our elastic numerical simulations come from two sets of ground motions, recorded during two aftershocks of the Athens 1999 event. The instruments were installed in the free field, two at a site $x \approx 300m$ from the crest, and one at $x \approx 10m$ from the crest. The two major aftershocks have provided the empirical transfer function spectra that are plotted in Fig. 9. Since the seismographs were placed at locations with different soil property characteristics (profile B for the first two and C for the later), the Fourier spectra evaluated from the aftershock accelerograms have been initially divided by the one-dimensional transfer function for each profile. For the recorded peak accelerations being of the order of 0.015g, the low-strain dynamic soil properties were used for this purpose. Thus, the variability arising from soil-column flexibility effects has been eliminated.

For the class-A prediction shown in Fig. 9, the stratigraphy of profile C has been used as the background medium stiffness of a Gaussian stochastic field with $\theta_i = 2.5m$ and $\theta_z = 15.0m$, extrapolated from the geostatistical data of an adjacent site. For the denormalization of the field, a constant standard deviation $\sigma = 0.15 F_r$ has been adopted. The mean and standard deviation of the numerically predicted transfer functions from 20 realizations of the stochastic field at $x = 10m$ are shown in Fig. 9. For the simulations, a Ricker wavelet with central frequency $f_0 = 5Hz$ has been used.

It can readily be seen that the recorded and computed results are in very good agreement, offering strong support to our conclusions. Nevertheless, what should be highlighted herein is that the incorporation of spatial small-strain stiffness variability and correct calibration of Rayleigh damping coefficients has proven to be of great importance for the representation of site conditions and subsequent successful prediction of topographic amplification.

**INELASTIC SIMULATIONS**

**One-dimensional analyses:** The effect of local soil conditions in modifying the intensity and frequency characteristics of ground shaking in Adàmes is first investigated by means of 1D inelastic wave propagation analyses. The far-field profiles A, B and C are subjected to the six strong-motion time histories and the surface response is computed in the frequency-domain using an iterative equivalent linear algorithm, and in the time-domain, by incremental nonlinear finite element simulations. For the former, a modified solution was adopted in which the strain-compatible soil properties are frequency-dependent, thus avoiding artificial damping of the high-frequency low-amplitude components of motion (Ref. [6]). For the latter, we used the multi-yield plasticity soil model implemented in the computer code DYNAFLOW (Ref. [7]). For consistency, the parameters controlling the shear behavior of the constitutive model were calibrated to yield the modulus degradation curves (Ref. [8]) used in the equivalent linear solution. The surface response computed by means of the two approaches, is found to be in remarkable agreement.

From the ensemble of the analyses performed, the following conclusions are drawn:

(i) Profile A being the stiffest of the three sites, shows an appreciable degree of amplification in the period range of $T < 0.3sec$, where both PGA as well as spectral acceleration (SA) values increase by an average of about 25% compared to the rock-outcrop input motion. However, soil amplification does not alone suffice to explain the observations. Topography and local soil conditions have equally contributed to the observed damage distribution at this site, which was more intense next to the crest. In fact, for this stiff and relatively homogeneous profile, the moderate damage intensity can be even justified by means of our elastic 1D and 2D analyses (recall $a_{yy}/a_{ff} = 1.3$ for profile A).

(ii) Profile B is softer than profile A, and simulations show larger amplification over a wider period range. Computed PGA values are in the range of 0.30g – 0.40g, and the highest SA reaches 1.50g at $T \approx 0.2sec$. Evidently, there is a pseudo-resonance condition occurring at this period: the fundamental period of the soil column ($T_{soil} \approx 0.2sec$ from the surface/rock-outcrop transfer function) nearly coincides with the dominant excitation period ($T_{input} \approx 0.2sec$). The dominant role of soil conditions becomes evident for this site, where the damage intensity was similar next to the crest and in the far-field.

(iii) Profile C is the softest of the three sites. The fundamental natural period of the soil deposit at the last step of the iteration process is estimated $T_{soil} \approx 0.72sec$, whilst most of the rock-outcrop excitations have much smaller dominant periods, $T_{input} \approx 0.1-0.2sec$. Hence, no increase or even deamplification is expected in PGA and in SA values due to local soil conditions for $T < 0.25$ sec, a fact which was confirmed by our results. On the other hand, the spectral
amplification predicted for periods 0.4 - 0.6 sec, could be substantial if the input motion were rich in such relatively long-period components. In summary, moderate elastic topographic amplification of 30% and 1D inelastic soil deamplification do not justify the observations for this profile, characteristic of one of the most heavily damaged regions in the 7-9-99 earthquake.

Two-dimensional analyses: We next perform 2D inelastic simulations and investigate the effects of material softening on the 2D amplification of surface motion. To simulate the inelastic soil response, we perform: (i) 2D elastic analyses with strain-compatible soil properties computed at the last iteration of the 1D iterative solution, and (ii) time-domain 2D nonlinear analyses using the multi-yield plasticity model. The surface response is again normalized by the far-field motion, which was found to be consistent for the two methods. A more useful measure of topographic amplification in the frequency domain is the response spectral ratio of the 2D horizontal acceleration component to the corresponding far-field response. In the ensuing, we shall refer to this ratio as Topographic Aggravation Factor (TAF). The mean TAF at $x = 20m$ from the crest is plotted in Fig. 10 as a function of period ($T$), for profile C and the ensemble of strong input motions.

As can readily be seen, the elastic and equivalent linear solution yield very similar spectral amplification values, whereas the inelastic solution shows significant enhancement of the high frequency components that is not predicted otherwise. This can be justified when we consider that the incremental variation of strain-compatible soil properties introduces a-posteriori randomness in the original horizontally stratified profile that has been shown to favor amplification of short wavelength components. It is indeed in the high-frequency regime that theoretical elastic models fail to predict measured amplification levels in the field. Note also that the elastic finite-element solution is shown to be sensitive to the correct selection of Rayleigh damping coefficients, which when calibrated for the mean frequency of the input motion artificially attenuate the high-frequency components.

For larger periods ($T > 0.2sec$), the spectrum of TAF shows that in the period range $0.2sec < T < 0.4sec$, where no 1D amplification occurs for the particular profile, topography effects are negligible. They become important again in the period range $0.4sec < T < 0.6sec$, which coincides approximately with the so-called topographic frequency (see Ref. [5]), determined from the location where maximum amplification of motion behind the crest occurs (recall that this is $h / \lambda_0 = 0.2$ for a homogeneous soil profile). For the stratified soil configuration, this can be approximated by $5h / \bar{V}_s$.

Amplification of high-frequencies is more pronounced when material heterogeneity (a-priori randomness) is also introduced in the simulations. A more realistic random small-strain stiffness field is here simulated as a non-Gaussian stochastic field, where the theoretical correlation structures have been fitted to available geostatistical data from an adjacent site (Ref. [9]). The spatial distribution of peak surface response is shown in Fig. 11 for profile C. The spectrum of TAF at $x = 20m$ from the crest is compared to that obtained from the inelastic wave propagation analysis of the horizontally stratified configuration in Fig. 11.

The erratic surface response, which is substantially amplified and more confined in the vicinity of the crest, is consistent with the enhancement of high-frequencies, when material heterogeneity and inelastic soil behavior are modeled. Ref. [9] illustrates that for 1D conditions, strong motion input introduces material yielding that is prominent in the vertical direction and overshadows the small fluctuations of the stochastic small-strain field, yielding the horizontally stratified configuration adequate for seismic response analyses. This is no longer valid for 2D wave propagation analyses, where the localization of material yielding is controlled by diffracted rather than direct waves and does not restore the background medium stratigraphy when inelastic effects occur.

Even more important for the justification of the damage distribution in site C is the amplitude of the vertical
acceleration component, which attains values 0.8-1.0 $a_{ff}$ near the crest. This is consistent with the results of our parametric analyses that show amplification of the parasitic response for a soft surface layer.

**Nonlinear soil-structure interaction**: The response of a rigid surface structure founded next to the crest is here simulated by means of 2D analyses. A schematic illustration of the configuration is shown in Fig. 12.

For relatively soft soil formations, repeated loading on structures creates a zone of yielding and inelastic deformation beneath the foundation. This reduces the effective dynamic impedance (radiation damping) of the semi-infinite domain and creates resonant frequencies at which the structural motion is amplified. Since material yielding is expected to be associated with seismic wave propagation, the subsequent response of a structure on a soil profile that exhibits strain softening, is expected to be altered.

On the other hand, upon incidence of seismic waves, soil deformations impose subsequent dynamic displacements to the foundation and the supported structure (so-called kinematic interaction). In turn, this induced motion of the super-structure generates inertia forces that result in dynamic forces and moments at the base, subsequently transmitted into the supporting soil. Therefore, additional deformations are imposed to the surrounding soil while additional waves emanate from the soil-foundation interface (so-called inertial interaction).

For the stiff soil formations in Adámes, altering of the response at the location of the structure is shown to be governed by kinematic interaction phenomena, namely the inability of the structure to follow the strongly differential surface response. As a result, frequency components of the horizontal response whose wavelengths are comparable or shorter than the dimensions of the structure are filtered. Nevertheless, the vertical acceleration is almost unaffected by the presence of the stiff structure and moreover, the differential surface ground motion imposes additional rocking loading.

Results are shown for the stratigraphy of profile C in Fig. 12, where the spectrum of TAF at the centerline of the structure is compared to the free-field response at the same location. Note that the high-frequency components of the response are geometrically filtered, yet for higher periods, the frequency content of motion is practically unaffected by the presence of the structure. This verifies that no significant inelastic effects occur as a result of the structural static loading or inertial soil-structure interaction.

**CONCLUSIONS**

Using a case study from the Athens 1999 earthquake, we have shown that: (i) despite the detrimental diffraction potential of the cliff, geometry could not alone predict the level of topographic motion amplification, (ii) even stiff soil sites (with average $V_s = 400$ m/sec of the top 30m) can substantially amplify seismic motions, (iii) soft surface layers significantly aggravate the amplitude of parasitic acceleration, which cannot be neglected for design purposes, (iv) weak motion data can be successfully used as a valuable guidance in reconnaissance studies, yet are not adequate to describe topography effects associated with strong motions, (v) 2D inelastic soil response introduces localized patches of yielded material, which equivalently to a random medium, amplify high-frequency components and further enhance the vertical response, (vi) soil-structure interaction on stiff soil deposits filters the high frequencies of the horizontal motion.

The normalization of the 2D response to the far-field allows the decoupling of soil and topography effects in the estimated response. With an adequate number of strong-motion case studies, the proposed Topographic Aggravation Spectrum can potentially be used for the development of a simple rule for the estimation of topography effects and pseudo-static slope stability analyses.

**REFERENCES**


