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SEISMIC RESPONSE ANALYSIS OF HISTORICAL TOWNS RISING ON ROCK SLABS OVERLYING A CLAYEY SUBSTRATUM

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ABSTRACT

Two case histories are presented which refer to the historical towns of Orvieto and Bisaccia, both located on top of rock buttes overlying a more deformable clayey substratum. The comparison of the two case histories indicates that apparently similar geological conditions do not lead to the same type of seismic response. In fact, the specific physical and dynamic properties of the substratum and the overlying slab can determine different seismic behaviour at the hill top and at the rock-clay interface. In particular, at Bisaccia a deamplification of the seismic motion at the hill top was predicted, as well as the development of excess pore pressures in the clay deposit underneath the conglomerate. On the other hand, at Orvieto significant amplification of surface motion is expected, due to the impedance contrast between the different pyroclastic materials of the rock slab and to the topography effect at the slab edge as well.

INTRODUCTION

In Italy several historical towns rise on top of rock buttes overlying a more deformable clayey substratum. This geotechnical situation has not only a relevant influence on the stability conditions at the margin of the rock slab but also affects the seismic response at the top of the hill.
In this context two case histories are presented, which refer to the historical towns of Bisaccia and Orvieto, respectively located in Southern and Central Italy. Bisaccia was built on a conglomerate slab resting on fissured overconsolidated sheared clays; Orvieto rises on top of a pyroclastic rock butte overlying overconsolidated clays. In both cases, the interaction between the rock slab and the underlying clay formation, produced by intense erosive processes, results in instability phenomena at the slab margin which threaten the peripheral areas of the town.
Recurrent strong earthquakes have induced dynamic actions that, according to historical and monitoring evidences, have superimposed to the static rock-clay interaction, often leading to local instability. Evaluation of magnitude and characteristics of dynamic actions requires a detailed seismic response analysis which has to account for specific morphological conditions and geotechnical stratigraphy at the two sites.

THE CASE HISTORY OF BISACCIA

Site description

The town of Bisaccia (Italian Southern Apennines, about 100 km NE of Naples) is located on a hill constituted of a slab of slightly cemented conglomerates, resting on a fissured clay shale formation (Fig. 1). The conglomerate slab is crossed by subvertical fractures, subdividing it into several blocks as wide as several tens of meters.
The conglomerates thickness is about 100m in the center of the slab (D-site) and reduces near to the borders. (Fig. 1a). In the areas surrounding the hill (B site) the thickness of the clay formation should be of more than 200 m (Di Nocera et al., 1995).
The current geomorphological setting is the result of an erosion process started about one 1 Myrs ago along the faults (Fig. 1b). This erosion process, which is still active, should have produced progressive removal of conglomerates, forming the two valleys that currently bound the hill (Di Nocera et al., 1995).
During Irpinia earthquake in 1980, an accelerometric station located on the hilltop recorded a peak ground acceleration of about 0.09g, which was accompanied by a relatively low degree of co-seismic damage to the buildings. Nevertheless, the town

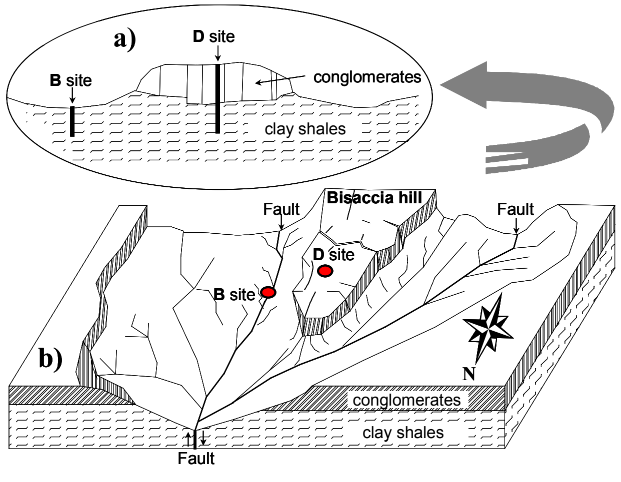

Fig. 1. Bisaccia area: a) EW section; b) geomorphological setting (after Olivares and Silvestri, 2001).

center was subsequently observed to experience progressive damages, which showed more significant than those detected immediately after the earthquake; this suggested to monitor the settlements of the slab and the pore pressure regime in the clay formation (Fenelli et al., 1992). The interpretation of the measurements suggested that the progressive evolution of damage with time could be associated to a post-cyclic recompression of the clay shales (D'Elia et al., 1985; Fenelli et al., 1992). Such a phenomenon was thought as a consequence of the dissipation of excess pore pressures induced by the dynamic deformation pattern of the conglomerate slab and underlying clay shales during the earthquake. Therefore, to verify the reliability of this hypothesis, a research program including experimental investigations and numerical analyses was planned. The main results of the dynamic analyses is resumed in the following. More details are available in previous works (Olivares, 1996; Lampitiello et al., 2001; Olivares and Silvestri, 2001).

Geotechnical model

The geometrical model assumed for the analyses is the EW cross-section reported in Fig. 2, which also shows the locations of verticals B and D, representing the different geotechnical conditions in the valleys and in the town center, respectively.
Some relevant properties of the materials are resumed in Table 1. The shear wave velocity for the conglomerates was obtained by cross-hole measurements taken at the seismic station site; that for the clays was obtained by the interpretation of laboratory tests on undisturbed samples of the clay shale (Olivares, 1996). Such tests yielded also the clay parameters required for the complete characterisation of non-linear behavior and shear-volumetric coupling, responsible for the pore pressure generation at the higher strain levels (Olivares and Silvestri, 2001). The other parameters, including the G/G_0-γ and D-γ curves for the conglomerates, and the shear wave velocity V_S for the bedrock, were taken from literature data on similar soils.

Table 1. Relevant geotechnical properties

Material	Unit weight γ (kN/m^3)	Shear wave velocity V_S (m/s)	Initial damping D_0 (%)
Conglomerate	21.6	1500	0.5
Clay shale	19.6	B site 120-350 D site 350-375	B site 4-1 D site 1
Bedrock	25.0	4720	-

Seismic input motion

The input motion used for the seismic response simulation of the hill was obtained by deconvolution of the EW horizontal component of the accelerometric record taken on top of the conglomerate slab during the 23.XI.1980 event (Fig. 3a). The deconvolution was carried out by means of SHAKE91 (Idriss and Sun, 1991), in the hypothesis of linear soil behavior, with the properties shown in Table 1.
The bedrock reference motion in all the analyses is illustrated in Fig. 3b; it shows a maximum amplitude as high as 1.5 times that of the surface record. The comparison between the amplitude Fourier spectra (Fig. 3c) shows that the bedrock motion is characterised by a higher energy content in the range of the higher frequencies (2-5 Hz), while a low frequency amplification (between 0.2-1 Hz) can be observed in the surface record.

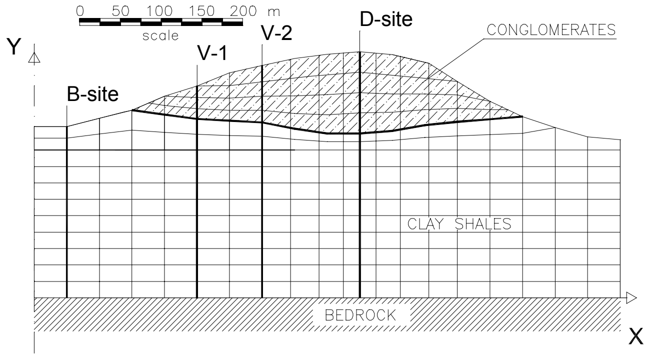

Fig. 2. Mesh representing the EW section of the Bisaccia hill used for the numerical modelling of the seismic response

Results

The seismic response of the vertical along Bisaccia hill town center (D site) was first simulated by 1D total stress analyses (SHAKE91), and then by 1D effective stress analyses (DESRA

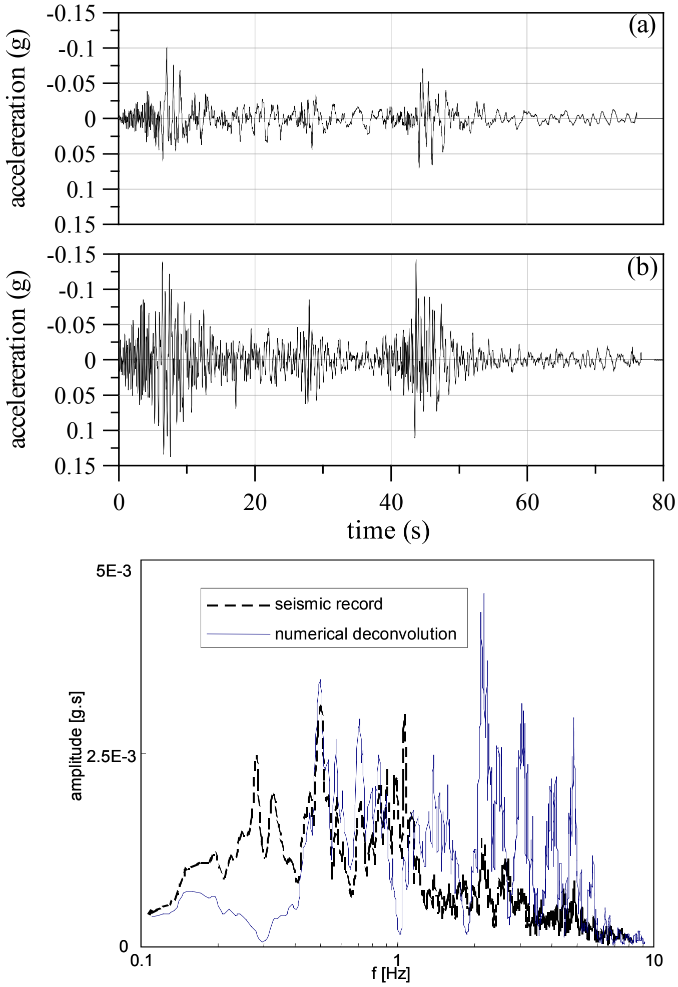

Fig. 3. Seismic input motion for Bisaccia hill: a) time record; b) after deconvolution; c) Fourier spectra

in the version updated by Matasovic, 1995). Two-dimensional total stress analyses reproducing the hill and the valleys (Fig. 2) were carried out through the FEM code QUAD4M, incorporating deformable bedrock (Hudson et al., 1994).

In Figure 4 the maximum acceleration and shear strain profiles resulting from non-linear 1D analyses with SHAKE91 and DESRA are compared to those obtained with QUAD4M for a simple vertical mesh (open symbols). The agreement among the three types of analyses is satisfying, in terms of both peak strain amplitudes and maximum acceleration.

The unusual reduction of amplitudes approaching surface shows that the conglomerate slab acts as a rigid mass on the top of the thick clay layer, limiting the seismic shaking at surface. If the stratigraphy is reduced to the simplified pattern of a rigid mass overlaying a deformable soil layer, a fundamental frequency of about 0.33 Hz is obtained, which is consistent to the range of low dominant frequencies characterizing the seismic record at surface (Olivares, 1996). Due to such low-frequency amplification and to the restraining effect played by the stiff conglomerate slab, the acceleration at surface is attenuated (Fig. 4a); on the other hand, the strain amplitudes within the clay layer are significantly above the volumetric threshold γ_v along the thickness of about the whole clay layer (Fig. 4b). As a consequence, the progressive accumulation of pore pressures in the thick clay layer was confirmed as responsible of the post-seismic subsidence observed (Olivares and Silvestri, 2001).

The effect of the variations in surface morphology induced by the erosion on the seismic response of Bisaccia hill can be inferred by comparing the peak amplitude profiles obtained from the analyses with QUAD4M, performed in the two hypotheses of 1D (open triangles) and 2D (solid triangles) geometry. In this latter case, the data refer to a so-called ‘heterogeneous’ characterization of the clay shale deposit, which assumes a variation of the initial equivalent parameters, G_0 and D_0, consistent to the different distributions of overburden stresses along the different verticals induced by the erosion (Lampitiello et al., 2001). Thus, in the 2D-case, peak accelerations and strains along the subsoil profile at the town center result amplified, due to the reduced lateral constraint determined by the geometrical absence of the stiff slab in the two lateral valleys.

Additional two- dimensional analyses with QUAD4M were performed with a ‘homogeneous’ geotechnical characterization of the clay shale, i.e. extending to the valley the mechanical profile adopted for the clay under the slab. Comparing the horizontal profiles of the surface peak accelerations and strains obtained in the two different 2D analyses (Fig. 5), a significant increase in the motion of the valleys is noted in the case of the ‘heterogeneous’ characterization. As a consequence, the response close to the free surface in the valleys is expected to be strongly affected by the reduction of stiffness and increase of damping originated by the swelling due to the erosion.

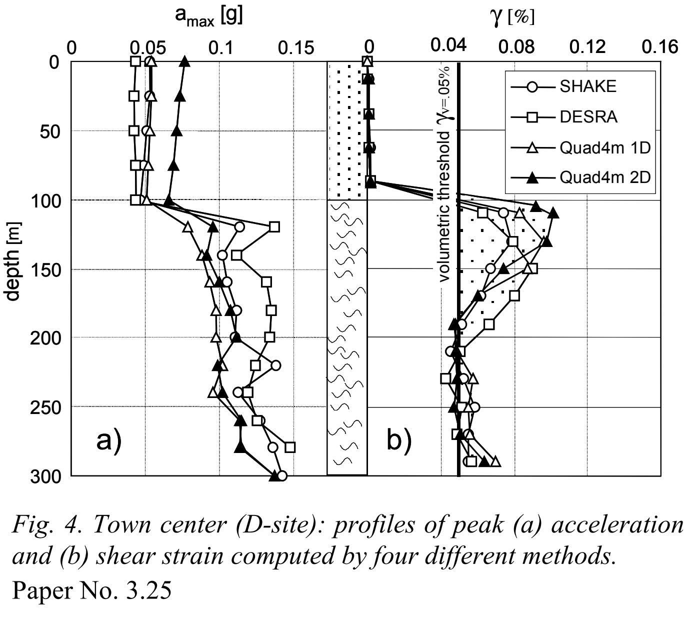

Fig. 4. Town center (D-site): profiles of peak (a) acceleration and (b) shear strain computed by four different methods.

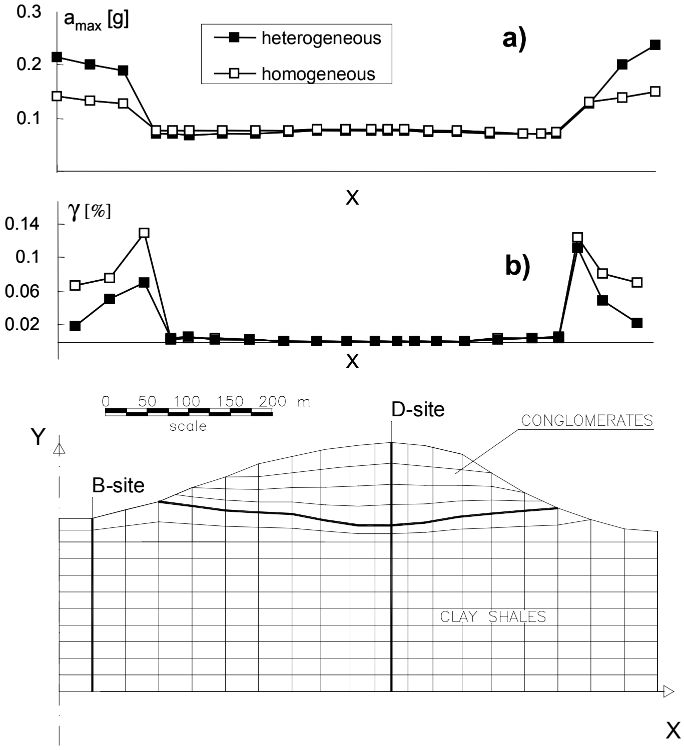

Fig. 5. Horizontal profiles of peak (a) acceleration and (b) shear strain computed by two different 2D analyses.

THE CASE HISTORY OF ORVIETO

Site description

The upper part of the Orvieto hill is formed by a slab of lithic tuff and weakly cemented pozzolana delimited by subvertical cliffs up to 60 m high (Fig. 6). The slab is approximately elliptical in shape (Fig. 6), with a maximum length of 1500 m in the WE direction and a maximum width of 700 m in the NS direction. The lower part is a truncated cone carved in an overconsolidated clay formation overlying the cenozoic bedrock located at a minimum depth of 200 metres (Di Filippo et al., 1991). Between the slab and the clay formation, a 5 to 15 m thick succession of weakly cemented silts and dense sands/gravels is interposed (Albornoz formation).

The slow deformation of the clay slope produced by the erosion, induces severe tensile stresses at the slab margin which are increased by the clay yielding at the cliff foot determining the fracturing of the slab margin which is subsequently involved in instability phenomena. Major instabilities consist of collapses of pozzolanic spurs and by sliding of large regularly jointed portions of the cliff. More frequent are block falls produced by toppling, sliding and tensile failure along sub-horizontal planes of tuff and pozzolana slices. The interpretation of historical data and a comparative analysis of seismic and landslide catalogues reveal that a number of falls can be related to seismic events. However, damages to structures are the most frequent seismic effects reported in historical sources.

Geotechnical model

Geotechnical data on pyroclastic materials were collected at the southern cliff, where stratigraphy is uniform over a long stretch. Boreholes were drilled, static and dynamic properties of materials were determined on the recovered cores and shear wave velocities were measured by means of a cross-hole test.

At the investigated site, a basal layer of lithic tuff is overlaid by the pozzolana which can be subdivided into a lower competent layer and an upper weak layer. The tuff and the competent pozzolana are cut into large prisms by vertical joints whilst the weak pozzolana is virtually massive.

Geotechnical parameters of tuff and pozzolana (Tommasi and Ribacchi, 1998; Rotonda et al., 2002) are reported in Table 2. Due to the massive structure of the deposit, in-situ and laboratory stiffness/velocity are very similar (Rotonda et al., 2002). In the tuff, V$_S$ values can be derived from laboratory data using proper values of bulk density accounting for in-situ water content.

Table 2. Geotechnical properties of pyroclastic materials

Material	Red Tuff	Competent pozzolana	Weak pozzolana
Bulk dry density (Mg/m^3)*	1.18	1.15	1.06
Shear wave velocity (m/s)*	1150	620	540
Shear wave velocity (m/s)$^{\#}$	-	550-650	470
Tensile strength (MPa)*	0.64	0.092	0.066
Uniax. comp. strength (MPa)*	4.52	2.28	0.90

* Laboratory tests on dry samples $^{\#}$ in-situ measurement

The stiff in-situ clay formation is covered by a slide debris blanket of remoulded and oxidized clay. At the top the stiff clay is softened and fissured with closely spaced joints which progressively disappear with depth. The thickness of the different "layers" varies widely over the slope. Geotechnical properties of the materials are reported in Table 3.

The geotechnical model is based on the stratigraphy of the southern part of the hill and on the morphology displayed in the longitudinal (WE) and transversal (NS) cross-sections (Fig. 6). However, stratigraphy differs from zone to zone within the hill and this can lead to different seismic responses.

Table 3. Geotechnical properties of the slope materials

Clay material	Stiff	Softened	Remoulded
Bulk density (Mg/m^3)	2.14	2.01	2.0
Natural water content (%)	20	23.5	27
Liquid limit	50	50	53
Plasticity Index	21	20	24
Undrained strength (MPa)	0.8	0.3	0.1
Shear wave velocity (m/s)	560-590	300-450	200-210

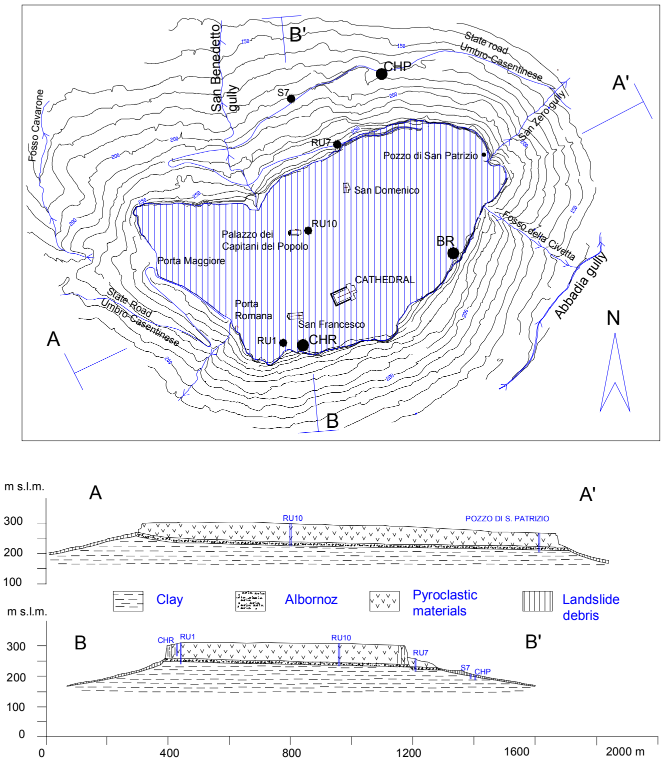

Fig. 6. Plain view and schematic cross-sections of Orvieto hill

One- and bi-dimensional total stress analyses were performed by means of SHAKE91 and QUAD4M, respectively. The 2-D model of WE section is sketched in Fig. 7. The slab is 1400 m wide and 60 m thick whilst the clayey slope is 100 m high with an inclination of 18°. The model of the NS section coincides with the previous one except for the width, which is 700 m. Both sections are symmetrical with respect to the center of the hill. In 2-D analyses, to minimise the effects of wave reflection from the side boundaries, they were extended horizontally 900 m away from the slope foot.

Based on the results of geotechnical investigations, it was judged that four different materials could describe the soil stratigraphy. From top to bottom, the slab consists of a 20 m thick pozzolana layer bearing on 10 m layer of competent pozzolana, which in turn overlies a 30 m thick tuff layer. Beneath the slab, a 200 m thick stiff clayey substratum is superimposed on the bedrock.

According to the laboratory and cross-hole measurements, the different layers were assigned constant values of mass density, ρ, and shear wave velocity, V$_s$ (Fig 7). It is worth noting that the combination between V$_s$ and ρ values yields singular impedance ratios between in-contact materials. In particular between clay

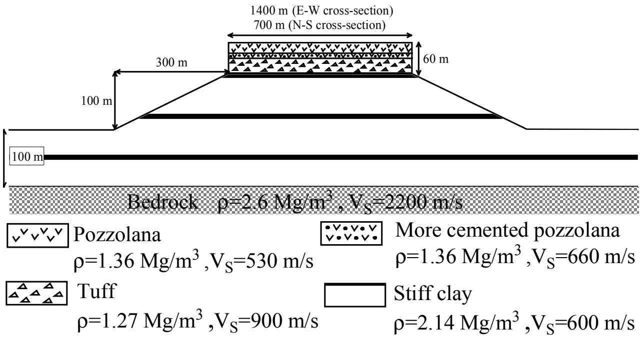

Fig. 7. Geotechnical model for numerical simulations

and tuff impedance ratio is 1.1; conversely impedance ratio values for tuff-to-pozzolana and competent-to-weak pozzolana are 1.24 and 1.27, respectively. This implies that the larger impedance contrast is not at the clay-slab interface but between the volcanic materials within the slab.
The G/G_0-γ and D-γ curves for each material were taken from experimental data published in the literature on similar materials.

Seismic input motion

As documented by historical sources, Orvieto suffered the effects of near-field as well as far-field earthquakes (Monachesi & Stucchi, 1997; Boschi et al. 1997). The strongest near-field event is the 1695 Bagnoregio earthquake (D=10 km, I_O=IX MCS) which also produced the highest observed intensity at Orvieto (I_S=VIII MCS). The majority of the events are far-field (D=70-80 km), located in the Umbria Apennines. The strongest are the 1328 and 1703 Norcia earthquakes (I_O=X MCS, I_S=VI MCS and I_O=X MCS, I_S=VI-VII MCS, respectively) and the 1751 Gualdo Tadino earthquake (I_O=X MCS, I_S=VI MCS). It is worth noting that a number of distant events (more than 80 km) were actually felt with appreciable intensity (I_S=VII-VIII MCS). In particular the 1915 Fucino earthquake (D=140 km, I_O=XI MCS) and the 1349 Aquila district earthquake (D~100 km, I_O=IX-X MCS).
For evaluating a credible rock outcropping motion for seismic response calculations an analysis of the historical seismicity of Orvieto and a seismotectonic study of the region (Muzzi et al., 2001) were carried out. Two controlling near-field (NF) and far-field (FF) seismogenic zones were identified, which are characterised by the following source-to-site distance, D, and maximum historically observed magnitude M_{max} : D ≤20 and M_{max} =5.9 km (NF); D ≥70 km and M_{max}=6.7 (FF).
Several rock outcropping accelerograms were selected from the world-wide data bank matching the required M_{max} and D values. From a comparison of the elastic response spectra, two accelerograms producing the maximum ground motion at the site in the frequency range of interest were chosen. For the near-field, the NS horizontal component of recorded motion at Cascia station during the 1979 Valnerina earthquake (Italy) was selected (PGA=0.15g). For the far-field, the NS horizontal component of recorded motion at Butler Valley station during the 1992 Cape Mendocino earthquake (CA, USA) was chosen (PGA=0.067g).

Results

Hill Center. For the longitudinal (WE) section, the comparison between 1D and 2D analyses is very satisfactory in terms of a_{max} and γ_{max} profiles, both for near-field and far-field conditions (Fig. 8). In the near-field, a_{max} slightly decreases within the clay, increases moderately between clay and tuff and then increases significantly between tuff and pozzolana, especially in the competent pozzolana (Fig. 8a). Peak acceleration varies from 0.12g at the bedrock to 0.22g at the free surface. The amplification ratio, i.e. the ratio of peak acceleration on the ground surface to peak acceleration at the bedrock, is 1.8. In the far-field, a_{max} increases slightly within the clay, is almost insensitive to the passage into the tuff and then appreciably increases between tuff and pozzolana. Peak acceleration increased from 0.05g at the bedrock to about 0.14g at the surface,with an amplification ratio of 2.8.

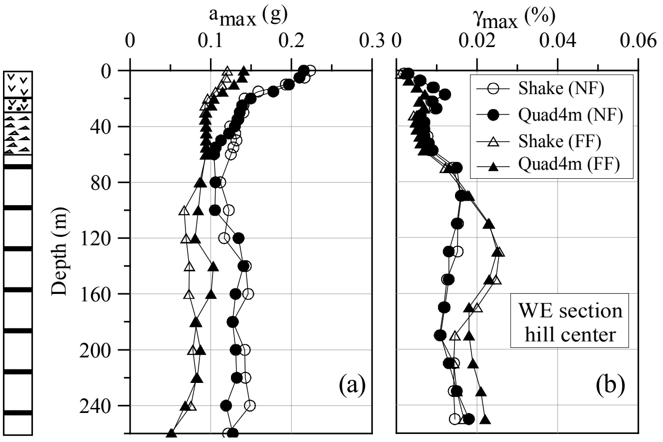

Fig. 8. Hill center: profiles of peak (a) acceleration and (b) shear strain computed by 1D and 2D analyses for WE section

Even though the peak shear strain is higher in the clay than in the slab (Fig. 8b), its magnitude does not exceed 0.02%. This value is smaller than the volumetric threshold for clays of similar plasticity (0.05%), thus suggesting that the increase of pore pressure related to shaking is negligible and therefore justifying a total stress analysis.
For the transversal (NS) cross-section , the comparison between 1D and 2D analyses at the hill center is shown in Fig. 9. The peak shear strain profiles obtained from 1D and 2D analyses are in fair agreement (Fig. 9b). Conversely, 2D analyses provide higher peak accelerations (Fig. 9a), especially in the slab, with the maximum difference at the ground surface. This behaviour is particularly apparent in far-field conditions (peak surface acceleration passes from 0.12g to 0.21g and from 0.22g to 0.34g in the far and near-field, respectively). These results, influenced by the smaller width of the slab in the NS direction, suggest that 1D analysis do not adequately account for the actual geometry.

From center to edges. The distribution of a_{max} along the ground surface is plotted in Fig. 10 for the WE section. In the near- field, a_{max} has practically constant value of 0.22g up to 200 m from the hill center and then increase up to 0.32 g at the cliff edge. At the

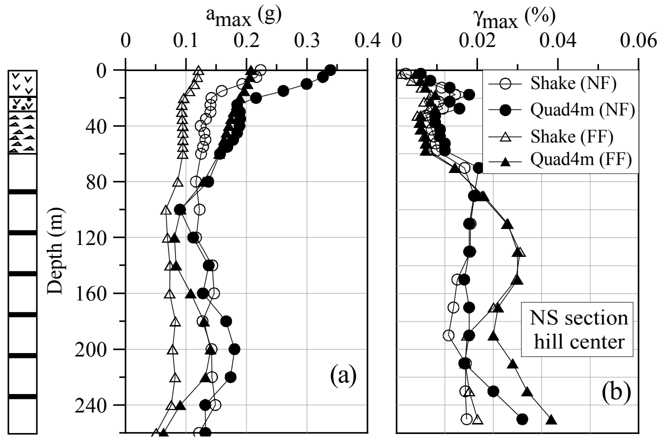

Fig. 9. Hill center: profiles of peak (a) acceleration and (b) shear strain computed by 1D and 2D analyses for NS section

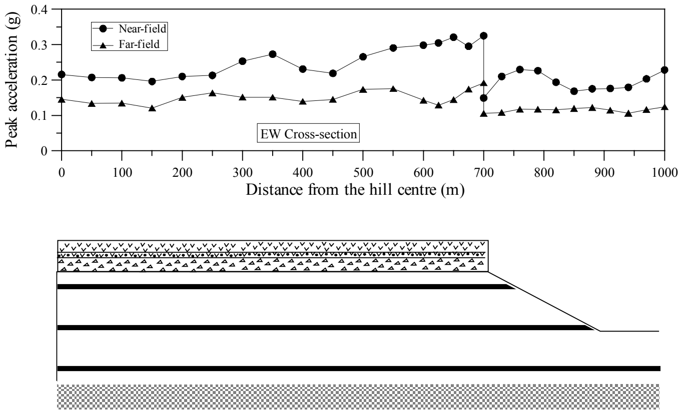

Fig. 10. Horizontal profiles of a_{max} computed by 2D analyses for WE section

cliff foot a_{max} abruptly decreases down to about 0.1g and slightly increases along the clay slope. For the far-field motion, variations of a_{max} along the ground profile follow a similar pattern but are significantly lower. For the NS cross-section, as already observed, the 2D geometry greatly affects the a_{max} distribution with maximum values at the center and at the edge.

CONCLUSIONS

The seismic analyses of two sites in Southern and Central Italy, where rock slabs overlie a more deformable clay substratum, evidence that specific physical and dynamic properties of the clay and rock materials can determine different behaviour at the hill top and at the rock-clay interface, even though apparently similar geological conditions are present.

In particular at Bisaccia an attenuation of the seismic motion at the hill top was predicted, as well as the development of excess pore pressures in the clay deposit underneath the conglomerate. The rigid mass of the conglomerate limits the seismic shaking at surface and makes the associated strains in the clay under the stiff slab so high as to induce excess pore pressures whose dissipation explains the progressive post-seismic deformations.

On the other hand, at Orvieto the impedance contrast between the different pyroclastic materials of the rock slab and the topography effect at the slab edge, result in significant amplification of surface motion. Combined effects of local soil conditions and topographic irregularities on the seismic ground motion were discussed by Kallou et al. (2001) for the ridge of Kifisos Canyon during the 1999Athens earthquake.

Analysis of literature on seismic response shows that the typical subsoil conditions are represented by a more or less gradual increase of stiffness with depth. As a matter of fact, in many seismic active areas frequently rigid formations overlie a more deformable substratum. Bisaccia hill is a typical example of this geotechnical situation. If no other mechanical characteristics of the materials are involved, since this geotechnical condition typically leads to the formation of isolated relieves, only a topographical amplification is expected and deformations are mainly due to the dissipation of excess pore pressures. However, in many weak rocks stiffness is coupled with relatively low density, thus producing singular impedance variations with depth, as it is found for Orvieto hill. In this case, in addition to the topographic effect, amplification generally occur when low impedance layers are superimposed to higher impedance ones. Further, except for very strong earthquakes, the development of excess pore pressures is not to be expected.

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