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A LABORATORY AND NUMERICAL INVESTIGATION ON A POST-SEISMIC INDUCED SETTLEMENT IN SOUTHERN ITALY

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ABSTRACT

In the years following the Irpinia earthquake (1980), the old town of Bisaccia, located on a conglomerate hill overlaying a thick clay formation, experienced a slow subsidence revealed by topographic measurements. The paper summarizes the results of the numerical simulations of the effects of the Irpinia earthquake on the Bisaccia hill. The input data for the analyses were the acceleration records of the seismic event at the site and the geotechnical characterization obtained by dynamic and cyclic torsional tests on undisturbed clay shales. The analyses confirmed the hypothesis that the town subsidence was caused by a post-cyclic soil re-compression as a consequence of the earthquake-induced pore pressures. In fact, the computed shear strains generated by the earthquake within the clay shale deposit often trespassed the volumetric threshold strain; the consequent pore pressure buildup should then justify the observed settlements.

BACKGROUND

The town of Bisaccia is located in the Italian Southern Apenines, on a hill about 100 km North-East of Naples. The hill is constituted of a slab of slightly cemented conglomerates resting on a fissured clay shale formation (Fig. 1). The conglomerate slab is crossed by fractures, generally vertical, subdividing it into several blocks whose width is of the order of several tens of meters.

The conglomerates thickness is about 100m in the center of the slab (D-site) and shows a reduction near to the borders. (fig. 1a). In the areas surrounding the hill (B site) according to Di Nocera et al. (1995) the thickness of the clay formation should be of more than 200 m. The current geomorphological setting of the area is the result of an erosion process that should have 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 bounding Bisaccia hill (Di Nocera et al., 1995).

After Irpinia earthquake in 1980, the town center experienced progressive damages, which showed more significant than those detected immediately 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 results of pore pressure measurements performed both in lateral valleys (B site) and in the clay formation below the slab (D site) are reported in Figs. 2 and 3. In site B the groundwater level is at ground surface. However, measurements carried out at a depth greater than 10 m show pore pressures lower than hydrostatic, and somewhere even negative (Fig. 2).

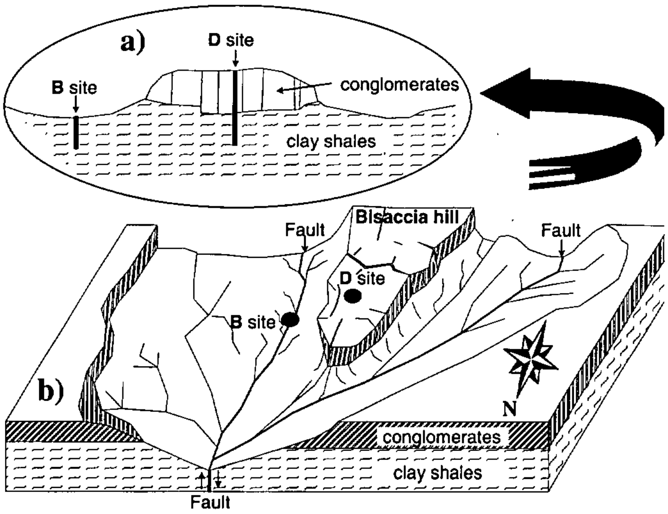

Fig. 1 Bisaccia area: a) E-W section; b) geomorphological setting (modified after Fenelli & Picarelli, 1990).

Such deficient values were related to the unloading process produced by erosion. In fact, due to the very low permeability of clays, the pore pressures equalization induced by stress release is much slower than the unloading process produced by erosion (Picarelli & Urciuoli, 1993).

Pore pressures measurements carried out in site D (Fig. 3) show that the water table is located at a depth of about 80m in the conglomerates. Moreover, a piezometer cell installed in clay shales at 149m depth (Fig. 4) shows that, after a first stage of equalization, the pore pressure right after the earthquake resulted greater than the corresponding steady state value, to which it gradually converged with time.

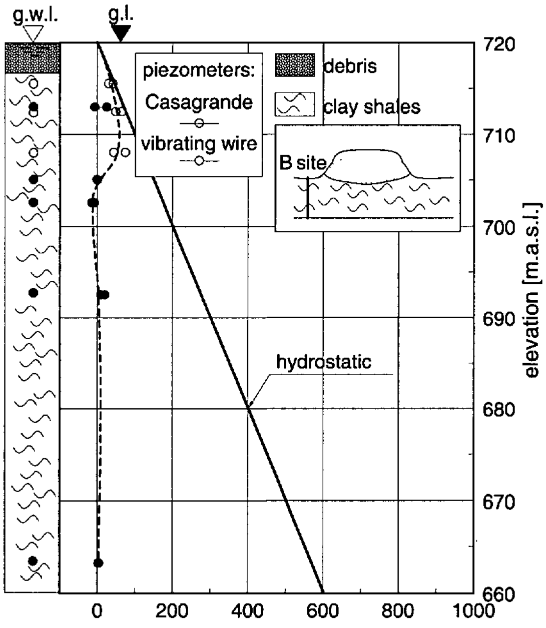

Fig. 2. B-site (lateral valley) ranges of pore pressure measurements in 1985-1996 (after Olivares, 1996).

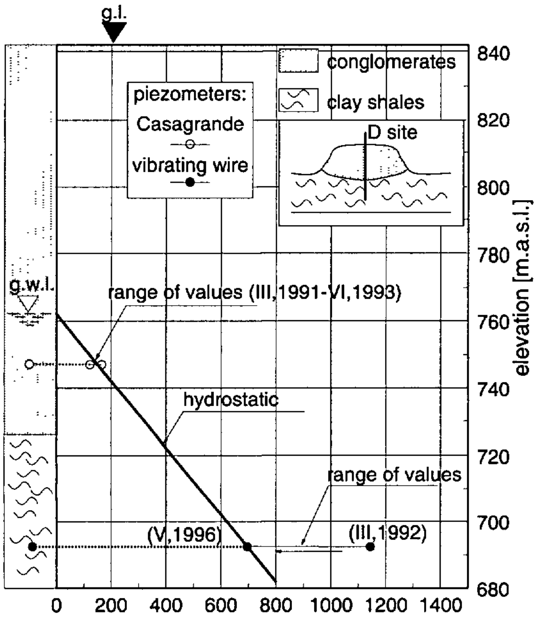

Fig. 3. D-site (town center): ranges of pore pressure measurements in 1991-1996 (after Olivares, 1996).

Different hypotheses were formulated to explain the results obtained in D-site (D'Elia et al., 1985; Fenelli et al., 1992; Picarelli & Urciuoli, 1993; Silvestri, 1993). This paper refers to the hypothesis according to which the excess pore pressures measured in site D are the result of the dynamic interaction between the conglomerate slab and underlying clay shales during the Irpinia earthquake. Such hypothesis is supported by the evolution of settlements measured in the town since 1981 to 1988 (Fig. 5). In fact, all the observed settlement-time curves exhibit the typical shape of a consolidation process, in agreement with the pore pressure decay in D-site. Both evidences suggest that the subsidence of Bisaccia town can be due to a post-cyclic recompression of the intensely fissured clay shales constituting the subsoil of the hill (D'Elia et al., 1985; Esu et al. 1987; Fenelli et al., 1992; Yasuhara, 1995).

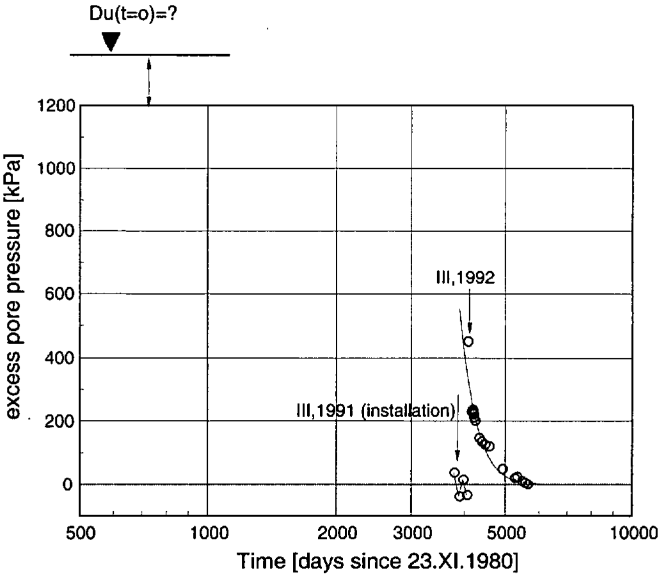

Fig. 4. Evolution of pore pressure measurements in D–site (after Olivares, 1996).

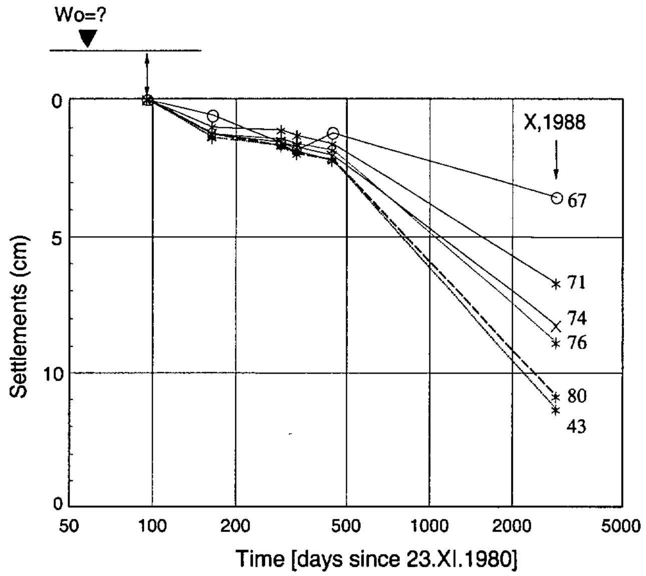

Fig. 5. Evolution of settlements the Bisaccia town after the Irpinia earthquake of 1980 (after Silvestri, 1993).

GEOTECHNICAL CHARACTERIZATION OF THE CLAY SHALE

To verify the validity of the above described hypothesis, a wide laboratory investigation on the clay shale was planned, including cyclic triaxial (CTX) and cyclic-dynamic torsional simple shear tests (Olivares, 1996). By means of these tests it was possible to define the soil parameters necessary for 1D and 2D numerical simulations of the earthquake effects. In particular, the results of resonant column tests were used to express the dependence of initial shear modulus, G_0, and damping ratio, D_0, on and stress state and history, as summarized in Fig. 6.

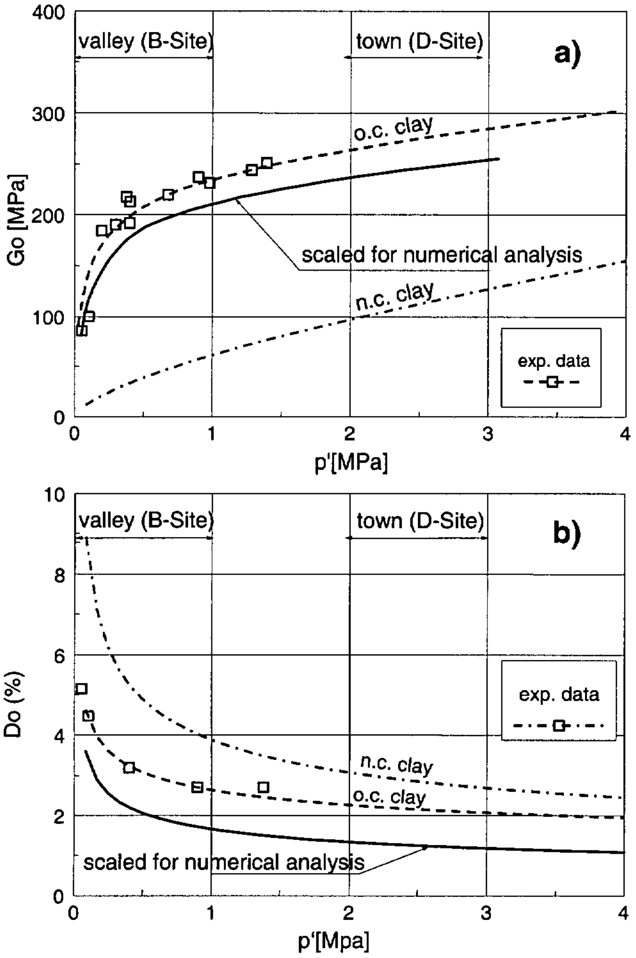

Fig. 6. Bisaccia clay shale: dependence of initial (a) shear modulus G_0 and (b) damping ratio D_0 on stress level and history (RC tests, Olivares, 1996).

The tests were performed on natural soil samples, isotropically consolidated at stresses ranging between 25 and 1380 kPa. The chain dotted lines in the figures refer to the behaviour of normally consolidated samples of the reconstituted clay (Olivares & Silvestri, 1995). The results obtained on the natural clay shale (square symbols, dashed lines) show higher stiffness and lower damping, due to the high overconsolidation pressure ($\approx$ 9.8 MPa). It is worth noting that, at the highest overconsolidation ratios (i.e. for stress levels lower than 0.5 MPa), the shear stiffness sensibly reduces as well as the damping seemingly increases, as a result of the swelling process (Olivares, 1996). Fig. 6 also shows the ranges of overburden stresses pertaining to the clay deposit underlying the conglomerate slab (D-site) and outcropping in lateral valley (B-site). Therefore, a more deformable and dissipative behavior is expected to have characterized the seismic response of the clay shale in the valleys, compared to that pertaining to the deposit underlying the conglomerates under the town area.

The analysis of initial stiffness and damping parameters obtained in torsional tests at increasing frequency and RC tests revealed a rate-dependency of this highly plastic clay, resulting in an overall increase of both G_0 and D_0 of about 9% per log cycle of frequency (Olivares, 1996). To define the actual soil parameters to be used in the numerical analyses, the suggestions by Olivares (1996) and d'Onofrio et al. (1999) were followed, consistently reducing the experimental values of both stiffness and damping (solid lines), to account for the higher loading frequencies of RC tests with respect to those typical of the reference earthquake record.

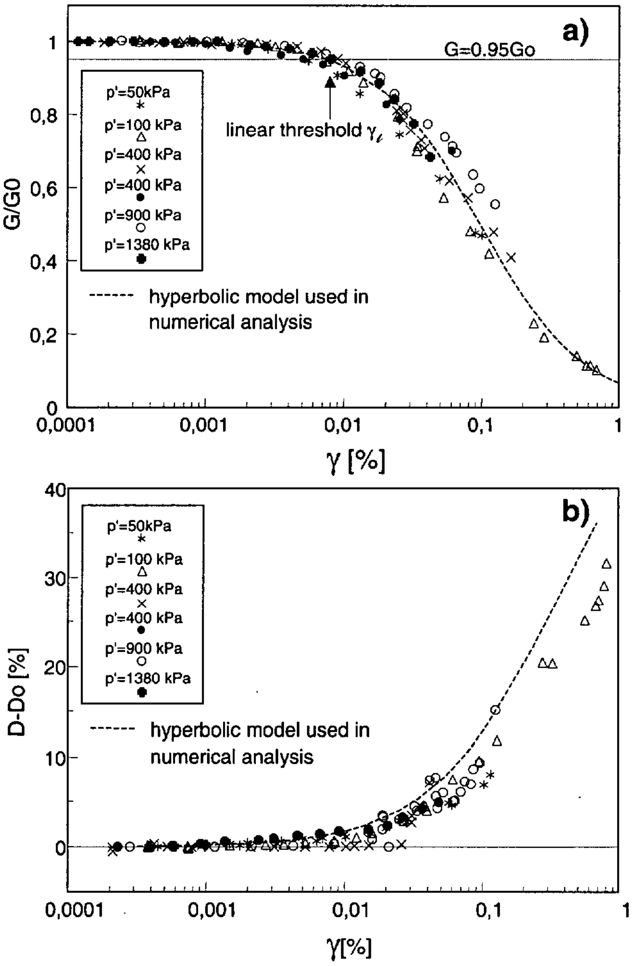

Fig. 7. Bisaccia clay shale: variation with shear strain of (a) normalized shear modulus and (b) scaled damping ratio (after Olivares, 1996).

Fig. 7 shows the results of the RC tests on the natural samples in terms of variation of the equivalent parameters, G and D, with cyclic shear strain amplitude, γ. The shear stiffness G is normalized to the initial value, G_0, and the damping ratio D scaled to its initial value, D_0. Notwithstanding the wide variation of consolidation stresses, all these curves appear quite uniform, showing a pseudo-linear behavior up to a linear threshold level, γ_l, of about 0.01%. This suggested to use an unique strain-dependent model to describe the behavior of Bisaccia clay throughout the whole deposit; the average dashed curves in fig. 7a,b were obtained averaging all the experimental data with the simple hyperbolic model, which was then consistently assumed for the analyses.

To account for the accumulation of pore water pressure during cyclic loading in the effective stress analyses, the results of cyclic laboratory tests were best-fitted by the model proposed by Dobry et al. (1985). This model expresses the normalized pore water pressure buildup, $\Delta u/p'_0$, as a function of cumulated number of cycles, N_c, and the net increase of cyclic shear strain, γ, with respect to the volumetric threshold shear strain γ_v as follows:

$$\frac{\Delta u}{p'_0}=\frac{pN_cF(\gamma-\gamma_v)^m}{1+N_cF(\gamma-\gamma_v)^m} \qquad (1)$$

Taking for γ_v the average value of 0.051%, resulting from both torsional and triaxial tests, the best fit values of the model parameters p, F, m resulted 0.35, 1.99, 0.93 respectively. The satisfying agreement between the model predictions expressed by eq. (1) and a typical set of experimental data collected in a cyclic triaxial test is shown in Fig. 8.

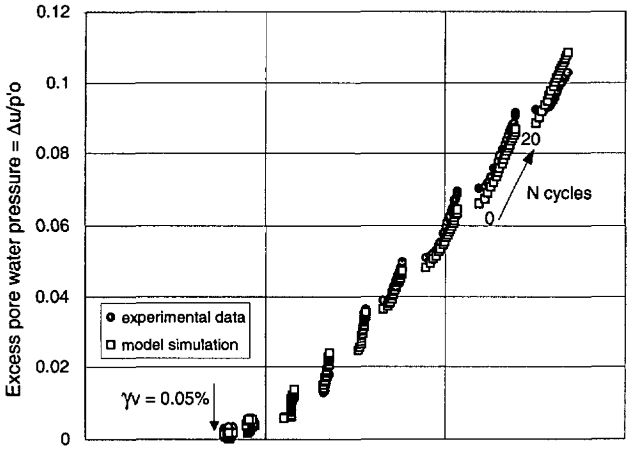

Fig. 8. Bisaccia clay shale: experimental and computed dependency of normalized pore pressure buildup on shear strain and number of cycles during a cyclic undrained triaxial test (after Olivares, 1999).

NUMERICAL ANALYSIS OF THE EARTHQUAKE EFFECTS.

The seismic input motion for the numerical simulation of the 23.XI.1980 event was obtained from the accelerogram recorded on the top of the conglomerate slab. The EW component was chosen, since it was thought as the most effective on the clay straining, because acting along the cross-section of Bisaccia hill (see Fig.1). The reference motion to be applied to the bedrock in all the analyses was obtained through downward deconvolution, performed with the code SHAKE91 (Idriss & Sun, 1991), in the hypothesis of linear soil behaviour.

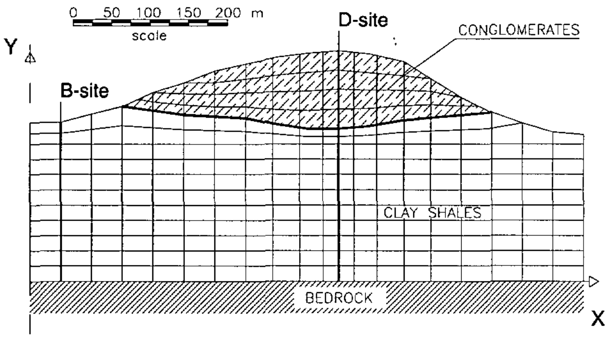

Fig. 9. EW cross-section of Bisaccia hill assumed for 1D and 2D modelling.

The geometrical model assumed for the analyses is the EW cross-section reported in Fig. 9, which also shows the locations of verticals B and D, representing the different geotechnical conditions in the valleys and in the town center, respectively. The properties of the bedrock (located at about 200m depth below the valley), and of the conglomerate are resumed in Table I. The unit weight for the clay was taken equal to 19.6 kN/m^3.

Table I. Properties of conglomerate and bedrock.

	unit weight γ (kN/m^3)	shear wave velocity V_S (m/s)	initial damping D_0 (%)
Conglomerate	21.6	1500	0.5
Bedrock	25.0	4720	-

The seismic response of the vertical along Bisaccia hill town center (D site) was first simulated by 1D total stress analyses (by SHAKE91), and then by 1D effective stress analyses (by DESRA, in the version updated by Matasovic, 1995). Two-dimensional total stress analyses of the mesh reproducing the hill and the valleys (Fig. 9) were carried out using the FEM code QUAD4M, incorporating deformable bedrock and adsorbing lateral boundaries (Hudson et al., 1994). All the numerical predictions discussed below have to be considered as quantitatively conservative, because the seismic input motion used for the simulations was obtained through a linear deconvolution. However, the results allowed to enucleate some interesting observations on the seismic vulnerability of Bisaccia hill.

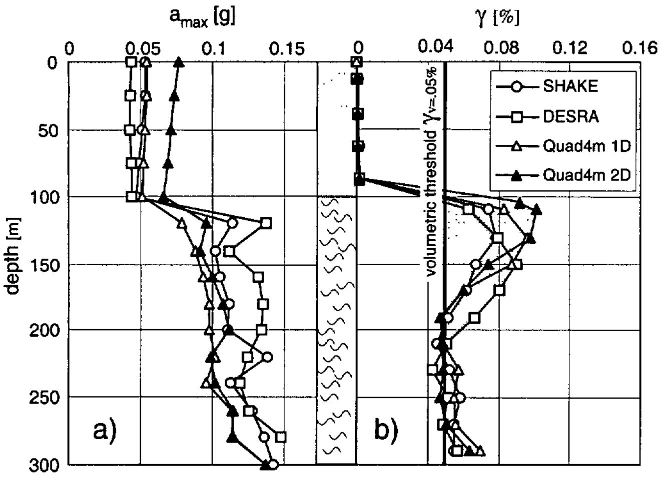

Fig. 10. Town center (D-site): profiles of peak (a) acceleration and (b) shear strain computed by four different methods.

Fig. 10 compares the maximum acceleration and shear strain profiles resulting from non-linear 1D analyses with SHAKE and DESRA, together with those obtained with QUAD4M for a simple vertical mesh (open symbols). The agreement among the three types of analyses is satisfying in terms of maximum acceleration, much better in terms of peak strain amplitudes.

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 resulted attenuated; on the other hand, the strain amplitudes within the clay layer appear significantly trespassing the volumetric threshold γ_v along the thickness of about the whole clay layer. As a consequence, a progressive accumulation of pore pressures in the thick clay layer can be envisaged as responsible of the post-seismic subsidence observed.

From the same plot, 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 double hypothesis 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, assuming a variation of the initial equivalent parameters, G_0 and D_0, following the different distributions of overburden stresses along the different verticals.

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.

The two-dimensional analyses with QUAD4M were then repeated referring to a so-called 'homogeneous' geotechnical characterization of the clay shale, i.e. assuming to extend to the valley subsoil the same mechanical profile adopted under the slab (homog. In Figure). Looking back to the experimental data reported in Fig. 6, the response of the clay shale close to the free surface in the valleys is expected to be strongly affected by the apparent reduction of stiffness and increase of damping originated by the swelling due to the erosion.

In fact, comparing the horizontal profiles of the surface peak accelerations and strains obtained in the two different 2D analyses (Fig. 11), a significant increase in the motion of the valleys is noted in the case of 'heterogeneous' characterization.

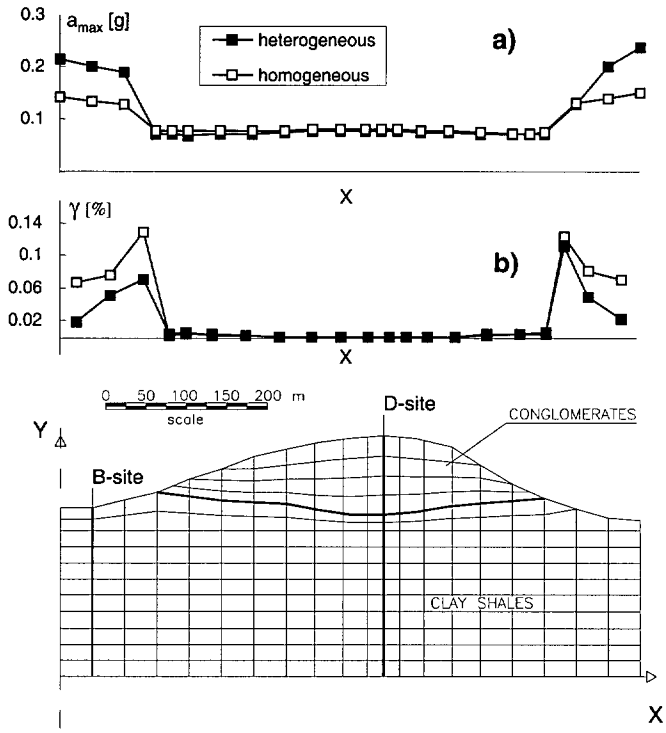

Fig. 11. Horizontal profiles of peak (a) acceleration and (b) shear strain computed by two different 2D analyses.

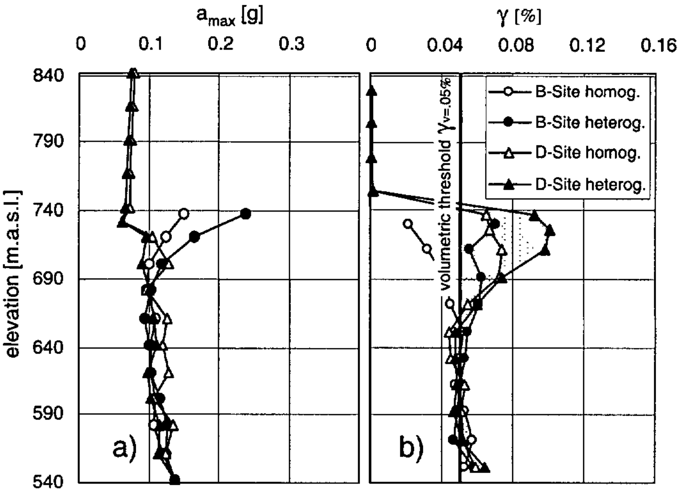

Fig. 12. Vertical profiles of peak (a) acceleration and (b) shear strain computed in the valleys and below town center.

If the response along the center hill vertical is compared to that at the valley (both as resulting from the 2D 'heterogeneous' analysis, Fig. 12), it can be noted that the peak motion amplitudes along the clay layer are practically the same along the lower part of the profiles, but diverge in proximity of the uppermost clay layer: more in detail, under the slab the accelerations are reduced and the strains show a local increase, while in the valley the accelerations show a significant increase and the strains remain approximately constant close to surface.

CONCLUSIONS

This study permitted to verify that the immediate and delayed motion of Bisaccia hill following Irpinia earthquake can be substantially ascribed to the intense erosion which originated the typical morphology of the area. The erosion effects on the seismic site response can be broadly ascribed to two aspects: a 'geometrical factor', that is the lack of lateral constraint on the hill ascribed to the absence of stiff conglomerate mass along the valleys; a 'mechanical factor', namely the variation of soil properties associated to swelling close to eroded surface. Geomorphological factors like these can be source of anomalous site effects occurring on sites with similar geometrical and geotechnical conditions, which are quite widespread in Southern Italy (Picarelli et. al, 1998).

These numerical results also support the hypothesis that the seismic shaking in 1980 was enough strong to produce a significant accumulation of pore pressures in clay shale formation under the conglomerate slab. This might have induced a post-cyclic recompression causing the subsidence-induced damage recorded in Bisaccia in the years following 1980. However, to better assess this conclusion, further improvements should be introduced into the analysis model: first, a more reliable estimate of the seismic input motion at the bedrock; then, a 2D coupled analysis model, able to predict the whole pore pressure field generated by the seismic shake; finally, a reliable mechanical model of the post-cyclic recompression of the clay shale, capable to justify the entity and rate of the observed settlements.

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