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INFLUENCE OF USING RECORDS AND ARTIFICIAL TIME-HISTORIES ON GROUND SEISMIC RESPONSE

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ABSTRACT

In spite of the increasing availability of strong-motion accelerograms worldwide, the scarcity or absence of records from strong earthquakes (M>6.0) in a given region, like Portugal, may lead to the use of artificial time-histories as input to dynamic analysis in geotechnical and structural engineering. Moreover, the artificial time-histories can be generated to be almost fully compatible with the elastic design spectrum defined by design codes.

The purpose of this paper is to compare the ground seismic response computed with two types of input motions: (i) records selected from a strong-motion database compatible with the near source scenario defined in the Portuguese code (RSAEP, 1983), and (ii) artificial time-histories compatible with both far and near source smooth response spectra. The records were selected from the European Strong-Motion Database (Ambraseys *et al*., 2000). The artificial time-histories were generated according to the procedure presented by Gomes *et al*. (2006).

The ground seismic response is evaluated by means of one-dimensional seismic response of a clay deposit. The soil behaviour is modelled by means of an advanced elastoplastic model.

The paper shows that the ground response in terms of peak acceleration and permanent displacement computed with both types of input motion have similar average values, while high scatter is associated with records against low scatter related with artificial time histories. Moreover, regardless the seismic scenario of the artificial time histories sets or records, good agreement was observed in the ground response, particularly in terms of PGA.

Keywords: artificial time-histories, records, ground seismic response, nonlinear numerical analysis

INTRODUCTION

Types of time histories

With the increasing availability of advanced analysis software, nonlinear dynamic analysis has become widely used for seismic design and performance-based analysis of above- and under-structures. However, to perform nonlinear analysis, time histories of motion are required.

Depending on the nature and on the goal of the application, the description of the seismic motion may be carried out using time histories (i) recorded in real events and if necessary modified, (ii) simulated through the physical simulation of source and travel path mechanisms, or (iii) artificial time histories generated to match a given response spectrum.

The recorded time histories rigorously reflect the influence of the characteristics of the seismic source, the rupture process, the source-site travel path, and the local site conditions (Kramer, 1996).

There is some tradition of using records of strong motions obtained during important earthquakes for the purpose of demonstrating the seismic resistance of particular structures. However, the isolated use of

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records is obviously not appropriate for that purpose. The databases of recorded strong motions available (for example, Ambraseys *et al.*, 2000) have made important progress in recent years. In spite of this progress, the recorded strong motions representative for different geologic characteristics, source-to-site distance and magnitude above 7 do not (yet) allow carrying out analyses with statistical significance.

The simulated time histories, developed from models for ground motion at the soil surface that are based on the physical process of earthquake generation and propagation, are fit for practical use. Nowadays, these models have reached a stage of maturity, and they have started to be applied systematically in geographical regions where data are not sufficient for a statistical approach to seismic hazards (Pinto *et al.*, 2004).

The artificial time histories are developed considering that they are samples of random processes. Generally, this procedure is used when the design action is provided in the form of a probabilistically defined response spectrum (Pinto *et al.*, 2004). This method is a simple, yet powerful, means for simulating ground motions. It is particularly useful for obtaining ground motions at frequencies of interest to earthquake engineers, and it has been widely applied in this context (Boore, 2003).

The main challenge in the development of artificial time-histories is to ensure that they are consistent with the target parameter and that they are realistic, i.e. their characteristics are consistent with those of actual earthquake.

In spite of the increasing availability of strong motion accelerograms worldwide, the scarcity or absence of records from strong earthquakes in a given region, like Portugal, may lead to the use of artificial time histories as input to dynamic analysis in geotechnical and structural engineering.

Seismic scenarios for Portugal

The seismic scenarios established for Portugal by design codes (RSAEP, 1983; National Annex to Eurocode 8, 2010) are two: the near source scenario has local Richter magnitude from 5.5 to 7.0 and source-to-site distance between 15 and 35 km, while the far source scenario has local Richter magnitude above 8 and source-to-site distance greater than 100 km.

To this study, the seismic parameters defined by both codes for Lisbon city are used. According to the RSAEP (1983), the peak ground acceleration (PGA) for the near source scenario (action type 1 - A1) is equal to 2.7 m/s^2, and is 1.6 m/s^2 for the far source scenario (action type 2- A2). Comparatively, the National Annex to Eurocode 8 (2010) establishes PGA equal to 1.70 m/s^2 for the near source scenario and 1.50 m/s^2 for the far source scenario.

The main difference between the seismic scenarios established in these codes is related to the type of data, since the seismic action established by the older code (RSAEP, 1983) was based on seismic hazard analysis developed by Oliveira (1977), which consider essentially low magnitude earthquakes, while for the most recent code (National Annex to Eurocode 8, 2010) larger strong motion data were available.

Objective

The purpose of this paper is to compare the ground seismic response computed using both artificial and recorded time histories compatible with the seismic scenario defined for Portugal as input motions.

The recorded motions, selected from the European Strong-Motion Database (Ambraseys *et al.*, 2000), are only compatible with near-source seismic scenario, as there no records available compatible with the far source scenario.

Two sets of artificial time histories compatible with the two seismic scenarios above referred were generated according to the procedure presented by Gomes *et al.* (2006), adopting the smooth response spectrum defined in the RSAEP (1983) code.

The evaluation of the seismic ground response was done through the one-dimensional model of a clay deposit. The soil behaviour was modelled by means of an elastoplastic model, taking into account progressive friction mobilization, Coulomb type failure, critical state and dilatancy/contractance flow rule.

The paper studies the ground response at the surface in terms of peak acceleration, permanent displacements and pseudo-response spectra.

RECORDED AND ARTIFICIAL TIME HISTORIES USED

Recorded time histories

The European Strong-Motion Database (Ambraseys *et al.*, 2000) was created to establish a freely accessible platform of a reliable strong-motion databank and associated database of seismological parameters of earthquakes in the greater European area and to provide high quality strong-motion and uniformly estimated seismological data from earthquakes in the European area.
This database contains more then 1000 uniformly corrected three-components strong motion records and response spectra from Europe and adjacent regions, coming from 432 earthquakes and 376 stations. For each record, information is provided on the earthquake (magnitude, location, focal mechanism) and on accelerograph station (location, distance to epicenter or to causative fault, soil conditions).
For the seismic scenarios defined for Portugal, the European Strong Motion Database (Ambraseys *et al.*, 2000) contains a relative small amount of records and only for the near source scenario. Therefore, the selection criteria adopted refers just to the near source seismic scenario:

- magnitude: from 6 to 7;
- source-to-site distance: from 15 to 35 km;
- local geology: rock and hard soil;
- building type: free-field;
- minimum horizontal PGA: 0.15 g.

Since the focus of this study is nonlinear analysis, very weak records were excluded adopting the minimum horizontal PGA criterion.
The number of records available in rock site was only 8, which justified the inclusion of hard soil on the selection criteria to achieve a total number of 24 records with 2 horizontal components each. The data obtained in the search came from 12 seismic events recorded in 21 stations. Figure 1 shows the magnitude-distance and magnitude-peak horizontal acceleration (PGA) distribution.

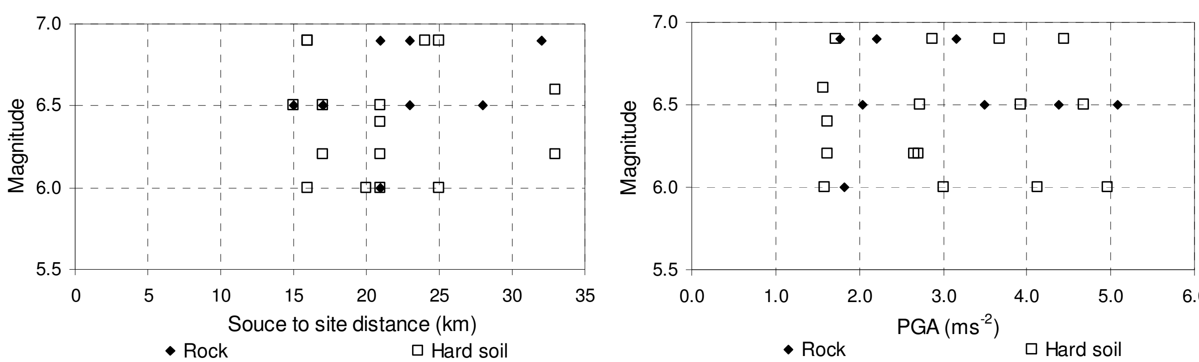

Figure 1. Magnitude distribution of the records according to ground classification, source to site distance and PGA.

Figure 2 shows the pseudo-response spectra (PSA) from the selected records, namely the average and the upper and lower envelope, along with the response spectrum from the older code (RSAEP, 1983) and from National Annex to Eurocode 8 (2010).

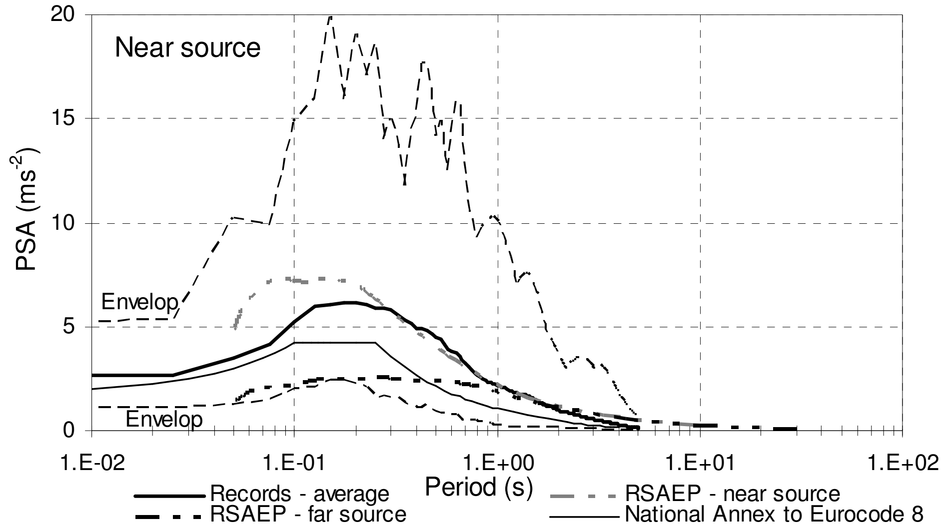

Figure 2. Pseudo-response spectra: average and envelops of all horizontal components of the records, RSAEP (1983) and National Annex to Eurocode 8 (2010).

It should be noticed that the average response spectra of the records is similar to the near source response spectrum defined by the older Portuguese code (RSAEP, 1983) for periods greater than about 0.2 s, in spite of the simple selection criteria adopted for records be based on magnitude and source-to-site distance. In addition, the records exhibit large variability of the spectral ordinates shown by the upper and lower envelops. As expected, the far source response spectrum defined by the older Portuguese code (RSAEP, 1983) is not similar to the response spectrum other sets.

Artificial time histories

The two sets of artificial time histories used in this work were generated to match both near and far source response spectra established by the older Portuguese code (RSAEP, 1983). These time histories were developed according to the procedure described by Gomes *et al.* (2006), based on random vibration theory. In order to correct non-physical shifts in velocity and displacement, the generated time histories were corrected.

A high number of spectrum-compatible time histories were generated for each seismic scenario. The selection of the artificial time histories was based on a simple criteria related to reference peak acceleration. Sixteen time histories were selected for near source scenario and twenty seven for the far source scenario. Table 1 shows the PGA's value statistics for the time histories selected for use in the numerical analysis.

As final remark, the mean PGA from the sets with the same seismic scenario (artificial and recorded) have very similar values. However, the coefficient of variation is high for the recorded time histories (55%) and very low (<3%) for both sets of artificial time histories.

Table 1. PGA's value statistics for the selected artificial time histories.

	Artificial		Recorded
	Near source (A1)	Far source (A2)	Near source
Sample size	16	27	48
Mean (g)	0.272	0.164	0.266
Median (g)	0.271	0.164	0.234
Standard deviation (g)	0.009	0.001	0.117
Coeff. of variation	3%	1%	55%

GROUND PROFILE AND NUMERICAL MODEL

Numerical model

The numerical model represents a gentle infinite slope. The model includes a column of quadrangular finite elements, to represent the soil deposit, overlying an elastic half-space (deformable unbounded bedrock). Figure 3 shows the finite element mesh.

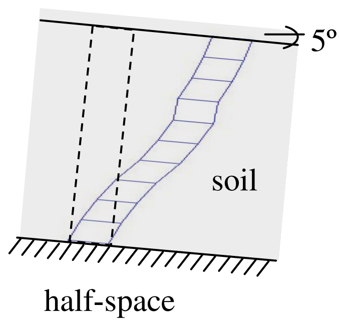

Figure 3. Finite element mesh: deformed shape.

The slope angle is 5° to obtain a model with some degree of asymmetry and to favour the accumulation of permanent displacement for one side. The soil layer is 10 m thick to obtain a model with a relatively low number of degrees-of-freedom.

In the analysis, as the lateral limits of the problem are considered to be far enough and only vertically propagating shear waves are studied, the response was assumed to be the free-field response. Thus, equivalent boundaries were imposed on the nodes of these boundaries, i.e. the normal stress on these boundaries remains constant and the displacements of nodes at the same depth in two opposite lateral boundaries are the same in all directions.

For the half-space boundary condition, paraxial elements simulating a "deformable unbounded bedrock" were used (Modaressi, 1987). The incident waves, defined at the outcropping bedrock were introduced into the base of the model after deconvolution. The bedrock is supposed to be impervious and the water level is at the ground surface. All the analysis performed considered the following properties for the half-space: shear wave velocity, V_s, equal to 500 ms^{-1} and mass density, ρ, equal to 2000 kg/m^3.

Elastoplastic model

An elastoplastic model was used to represent the soil behaviour on the top 10 m. The ECP's elastoplastic multi-mechanism model, developed by Aubry and co-workers (Aubry *et al*., 1982; Hujeux, 1985), commonly called Hujeux model, was used to represent the soil behaviour. This model can take into account the soil behaviour in a large range of deformations. The model is written in terms of effective stress. The representation of all irreversible phenomena is made by four coupled elementary plastic mechanisms: three plane-strain deviatoric plastic deformation mechanisms in three orthogonal planes and an isotropic one. The model uses a Coulomb-type failure criterion and the critical state concept. The evolution of hardening is based on the plastic strain: deviatoric and volumetric strain for the deviatoric mechanisms and volumetric strain for the isotropic one. To take into account the cyclic behaviour a kinematical hardening based on the state variables at the last load reversal is used. The soil behaviour is decomposed into pseudo-elastic, hysteretic and mobilized domains.

Soil modelled

The soil modelled is known as St. Iria da Azoia clay. This clay was tested under different loading paths by Santos (1999).

St. Iria da Azoia clay is a high plasticity alluvial soil of the Tagus river with Plasticity Index (PI) equal to 40% (Santos, 1999). In the plasticity chart, the clay is placed near the A-line and can be classified as CH or MH. The fine content is 99% and the clay content (<2 μm) is between 36 and 44%.

In this study the clay is simulated in the normal consolidated state, NC (OCR ≈ 1.2), and in the overconsolidated state, OC (OCR = 2.5 to 4.0).

The strategy to identify the model parameters and the cyclic response of the clay is detailed in Gomes (2009) and Gomes *et al*. (2010).

As reference, Figure 4 shows the model response and the experimental data from resonant column (RC) and cyclic torsional shear (CTS) tests for confining pressure of 25, 50, 100 and 200kPa. According to Santos (1999) the stiffness and damping curves are very close to each other, which show that they are not significantly affected by void ratio, overconsolidation ratio and confining pressure.

A good agreement can be found between experimental and numerical simulations up to nearly ten to the minus 3. Above this strain level, only the stiffness curve is relatively well simulated and damping is overestimated.

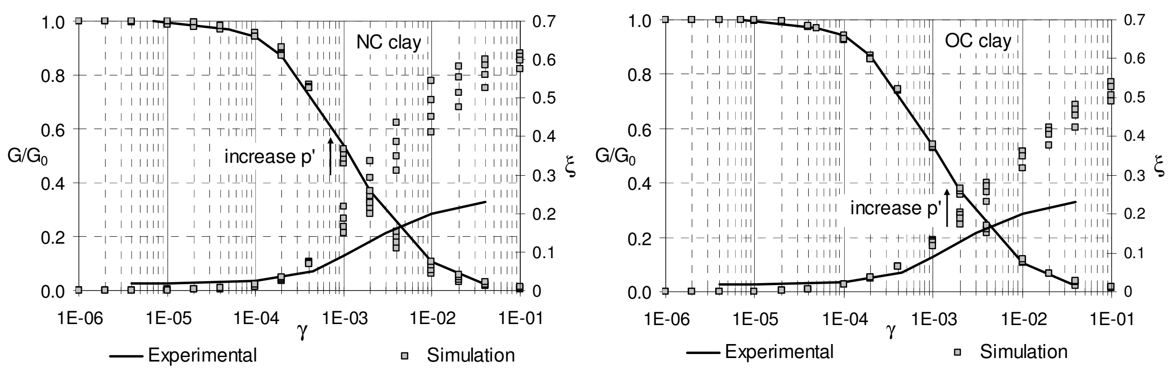

Figure 4. St. Iria Azoia clay (NC and OC): strain-dependent shear modulus and damping curves from experimental data (undrained RC and CTS tests) and numerical simulation.

RESULTS AND DISCUSSION

Peak ground acceleration

In this section, it is plotted the relation between horizontal PGA at soil surface against the PGA at rock outcrop. For the PGA's computed with the recorded time histories, the regression curve and R^2 coefficient are also presented (Figure 5). A reasonable mean of comparison of the analyses is done with the median relationship recommended for use in empirical correlations by Idriss (1990), based on recorded and calculated motion, in terms of peak accelerations. It should be emphasised that mainly the linear equivalent method was used in the calculations used by Idriss (1990).

All the data fall in the same range. It is noteworthy that independently of the seismic scenario and the type of time histories, there are good agreement between them.

The results obtained with artificial time histories are in general agreement with the results obtained with records, in spite of the seismic scenario of A2 (far source) artificial time histories to be significantly different from the other time histories (near source) used in the computations.

The regression curve for the results obtained with records have an evolution approximately similar to the Idriss curve, but with lower ordinates. The R^2 coefficient has values close to 0.50.

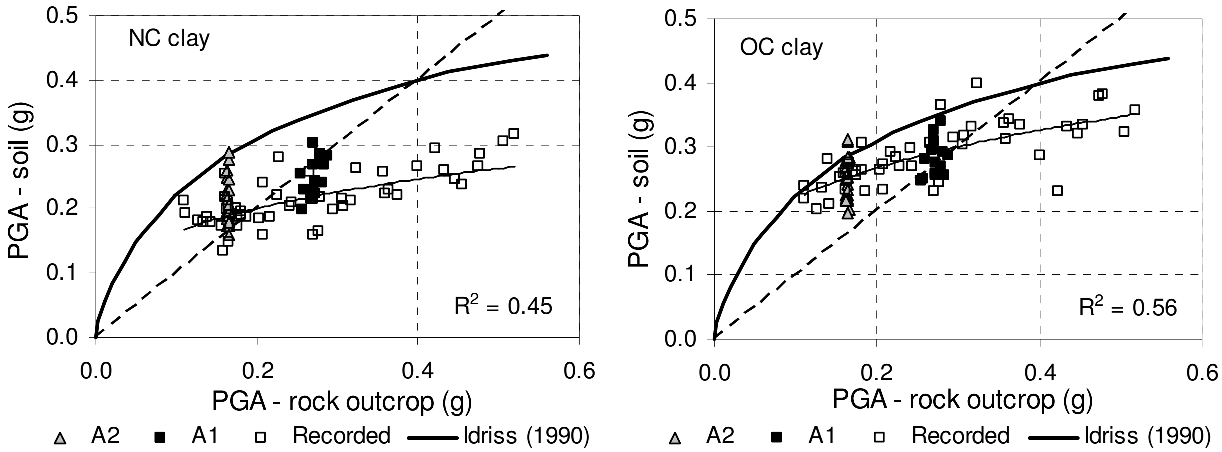

Figure 5. PGA at soil surface.

Table 2 shows statistical information related to results shown in Figure 5.

Table 2. PGA's value statistics at soil surface.

	Recorded (near source)		
	Rock outcrop	NC Clay	OC clay
Sample size	48	48	48
Mean (g)	0.266	0.216	0.287
median (g)	0.234	0.211	0.278
Standard deviation (g)	0.117	0.042	0.048
Coeff. of variation	44%	19%	17%
	Artificial – A1 (near source)		
	Rock outcrop	NC Clay	OC clay
Sample size	16	16	16
Mean (g)	0.272	0.248	0.284
median (g)	0.271	0.242	0.283
Standard deviation (g)	0.009	0.030	0.028
Coeff. of variation	3%	12%	10%
	Artificial – A2 (far source)		
	Rock outcrop	NC Clay	OC clay
Sample size	27	27	27
Mean (g)	0.164	0.208	0.251
median (g)	0.164	0.199	0.252
Standard deviation (g)	0.001	0.032	0.032
Coeff. of variation	1%	16%	13%

The recorded time histories has a coefficient of variation (COV) significantly higher (44%) than the COV of both artificial time histories (<3%). However, the response computed at soil surface with recorded time histories suffered an important decrease in the value of COV (17% and 19%), while for artificial time histories the COV increased (10% and 16%) for approximately the same level obtained with the recorded time histories.

As referred, both near source scenario time histories (artificial and recorded) have similar mean PGA value at rock outcrop (≈0.27g). Also, the response computed at soil surface have mean PGA value similar

for the OC clay (≈0.28g), while for NC clay the A1 artificial time histories produce higher mean value (0.248g) than the recorded time histories (0.216g).
Figure 6 shows the ratio between PGA at soil surface computed with the same time history in both NC and OC clay deposits, to point out the effect of the overconsolidation ratio on PGA at soil surface.

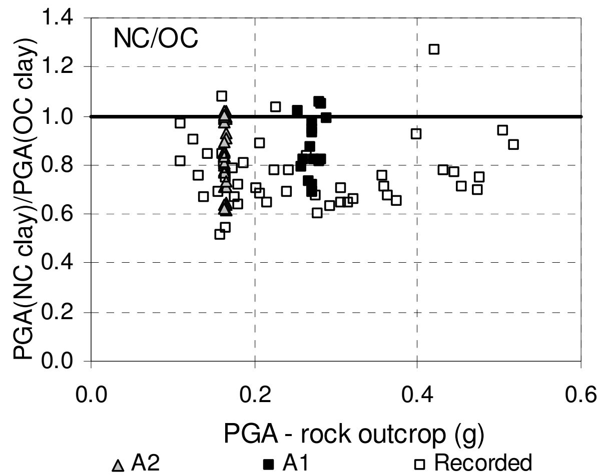

Figure 6. Effect of the overconsolidation ratio on PGA at soil surface.

In general, the PGA ratio is between 0.6 and 1.0, as OC clay produces higher PGA at soil surface than NC clay. It is important to notice that both near source scenario time histories produce similar mean PGA in OC clay deposit, but near source (A1) artificial time histories lead to lower mean PGA in NC clay deposit than in OC clay deposit.
The data related to far source (A2) artificial time histories fall in the range of the recorded time histories.

Permanent displacement

Figure 7 shows the permanent displacement computed at soil surface. For the permanent displacement computed with the recorded time histories, the regression curve and R^2 coefficient are also presented.
It is evident the dependence of the permanent displacement on the PGA at rock outcrop. The regression curve has associated R^2 coefficient with lower values (0.13 and 0.32) than ones obtained for PGA, which is a symptom of the large scatter associated to permanent displacement.
Similarly to PGA, in general all the data fall approximately in the same range. However, the data from artificial time histories tend to be above the regression curve obtained with recorded time histories data. Particularly for NC clay, the A2 (far source) artificial time histories lead to permanent displacements above the range of the other time histories.

Average pseudo-response spectra

Figure 8 shows the average pseudo-response spectra (PSA) from the time histories at rock outcrop and at soil surface.
The average response spectra of the several types of time histories used as input motion at rock outcrop have significant differences in the spectral ordinates (e.g., for period equal to 0.2 s, the spectral acceleration is nearly 3.5 ms^{-2} for A2 time histories and nearly 6.7 ms^{-2} for recorded time histories). Nevertheless, in general the average response at soil surface have spectral ordinates with similar values, particularly for the near source scenario (e.g., for the same period (0.2s), the average spectral acceleration obtained with both near source time histories is around 4.9 ms^{-2}, for NC clay, and around 7.1 ms^{-2} for OC clay).

The average response spectra obtained with A2 time histories lead to higher spectral ordinates at large periods (T > 0.6 s) and lower spectral ordinates at small periods (T < 0.6 s) in comparison with the response obtained with both sets near source time histories.

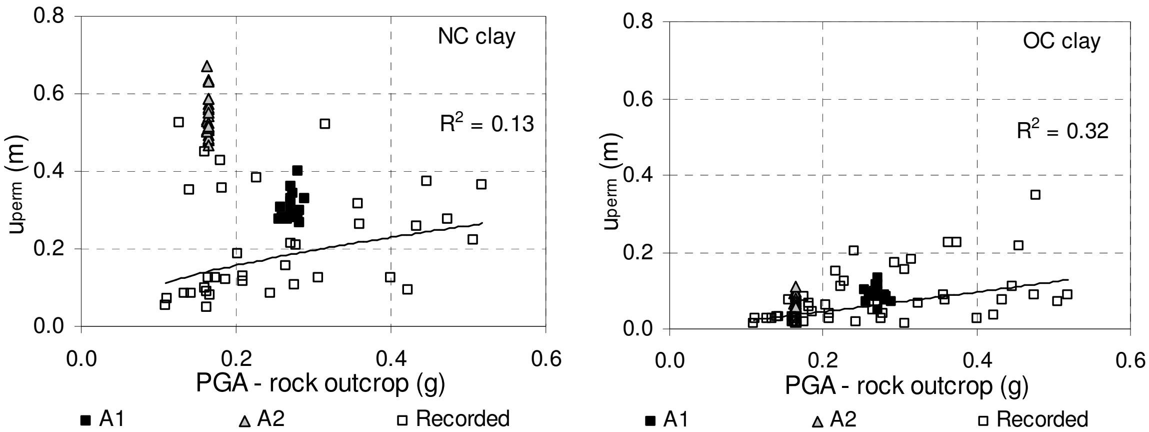

Figure 7. Permanent displacement at soil surface.

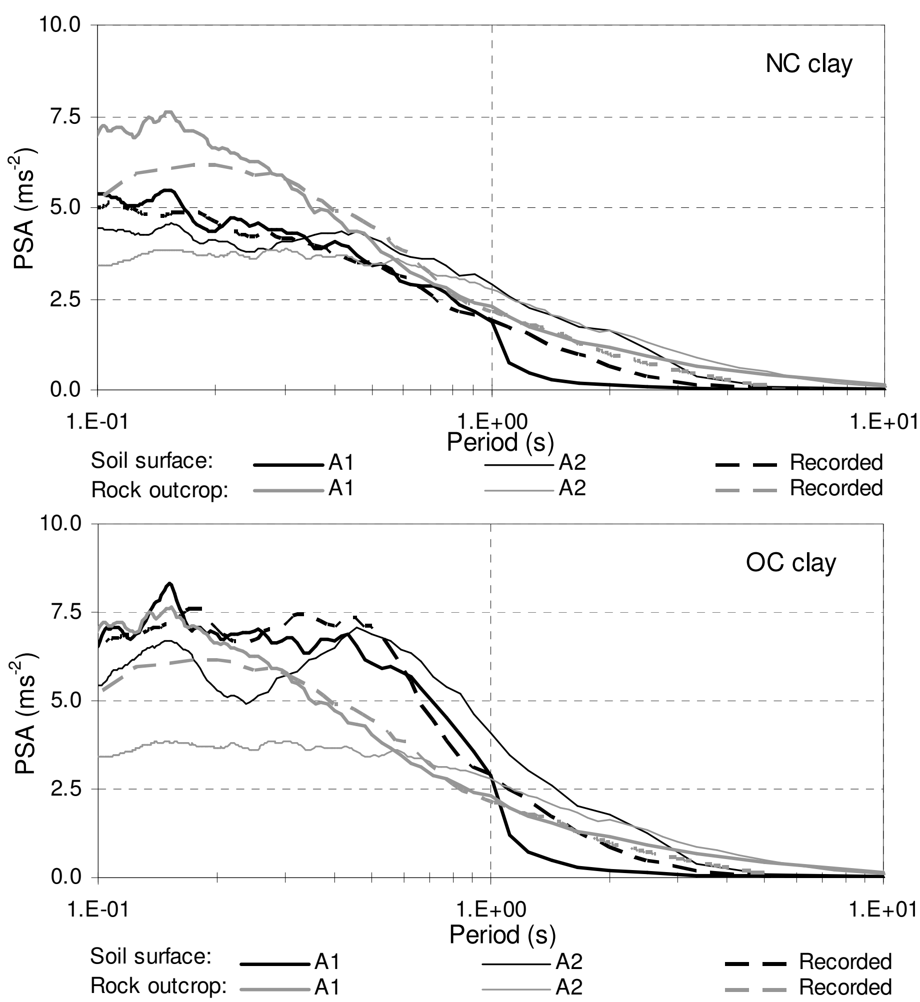

Figure 8. Pseudo-response spectra (PSA): acceleration at soil surface and at rock outcrop.

FINAL REMARKS

Generally, the response computed with artificial time histories (near and far source) is compatible with that computed with records, in terms of PGA. However, some differences can be pointed out in terms of permanent displacement and PSA.

The coefficient of variation of the PGA of the artificial time histories sets was very low, while for the recorded time histories that coefficient of variation was high. However, the ground response obtained with both types of time histories have similar values of coefficient of variation.

The PGA and the permanent displacement is found to be significant influenced by the overconsolidation ratio of the clay.

More studies are needed to assess the influence of using records and artificial time-histories on ground seismic response.

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