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Progetto di ricerca N. 6

Metodi innovativi per la progettazione di opere di sostegno e la valutazione della stabilità dei pendii

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6.3 STABILITÀ DEI PENDII

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Research Report – 3° Year Activity

1 INTRODUCTION

The response of a slope under seismic loading is determined by the temporal and spatial distribution of the seismic forces in the soil mass, which in turn depend on the characteristics of the seismic input and on the mechanical properties of the soil.

A number of different techniques exist to address this problem, each implying some level of approximation. Experience of the use of advanced numerical analysis is still somewhat limited, and it seems difficult to generalise the results of such complex analyses. An advisable approach would be that of carrying out the analysis of the same problem using a number of approaches characterised by different levels of complexity, in order to assess the reliability and robustness of the different procedures. In the third year of activity, different research groups were given the task of pursuing the study of the seismic behaviour of slopes using a number of different approaches, and investigating the possibility of using the results of the more advanced analysis as a guidance for a sound and reliable use of the simplest and most common analysis method, that still form the backbone of professional practice. In particular, in the research activity carried out in the third year the following tasks were included:

1. Updating of the Italian Database of strong-motion accelerograms and validation of new empirical attenuation laws for italian territory;
2. Regression models for estimating permanent displacements from seismic ground motion parameters;
3. GLE based multi-block model to evaluate slope seismic response;
4. Coupled analyses to evaluate seismic slope displacements;
5. Effect of soil stiffness on the seismic pseudo-static coefficient;
6. Seismic response analysis of slopes with translational sliding mechanisms;
7. Analysis of seismic behaviour of natural slopes using Finite Element Method (FE) with advanced constitutive relationships.

The objective of developing a simplified procedure for a reliable evaluation of the seismic performance of a slope was pursued by means of a number of tools, each referring essentially to a parametric evaluation of the permanent displacements of simplified slope schemes. Firstly, a database of Italian strong motion accelerograms was developed together with a site and source databank, to provide high quality Italian strong motion records with consistent and reliable associated seismic parameters (Task 1).

Using this database, a number of empirical relationships were developed for a preliminary estimate of earthquake-induced slope displacements (Task 2), and a code was developed for evaluating slope displacements induced by seismic shaking along sliding surfaces of general shape (Task 3). In this code, the mixed roto-translational mechanism is described via a multi-block model and account is taken for pore water pressure build-up and mass transfer occurring during motion. The code was checked by back-analysing the landslides reactivated by Irpinia earthquake of 1980.

Then, a parametric Newmark integration of the whole database was performed with the specific intent to evaluate, for a given seismic performance, the seismic coefficient to use in a pseudo-static calculation. This study was timely, as it was possible to include some results in a new version of the Italian building code (D.M. 14.01.2008).

The influence of soil deformability on slope response to earthquake loading was studied through one and two-dimensional equivalent linear visco-elastic analyses (Tasks 4, 5, 6) and with a limited number of two-dimensional fully coupled stress dynamic analyses (Task 7). The analyses considered simple idealised slopes and a few real earth dams.

The soil deformability brings about two somewhat contrasting effects, namely the amplification of the base motion and the non uniform spatial distribution of the inertia forces. The latter effect may lead to a substantial reduction of these forces, and can prevail when the wave length of seismic motion become comparable or smaller than the size of the sliding mass, and this may happen in large deformable volumes of soil, and for high-frequency seismic signals. Conversely, ground motion amplification prevails for small and stiff sliding masses excited by low-frequency seismic signals, and near the top of natural slopes or the crest of earth embankments, because of multiple reflection of the seismic waves.

To sum up, it may be stated that most of the research objectives were attained and that the main factors affecting the slope response to earthquake loading were recognised, their influence being isolated and evaluated.

2 ACTIVITIES

The activities of the 7 research unities of Linea 6.3 – Slope stability are a direct consequence of the research program planned in the previous years.
In the following, the main activities are presented for each of the tasks indicated in §1.

2.1 Updating of the Italian Database of Strong-Motion acclerograms and validation of new empirical attenuation laws for Italian territory

The main activitiy concerned the updating of the Italian database of strong-motion accelerograms. Appropriate source parameters (magnitude, hypocenter location, fault mechanism, etc.) associated with the seismic events were taken from the results of the S6 project developed in the framework of INGV-DPC research activity (http://esse6.mi.ingv.it) while fault solutions were taken from DISS (Database of Individual Seismogenic Sources) website (http://www.ingv.it/DISS/). Based on these data, all distances were re-calculated.
A major effort has been undertaken to improve the characterization of conditions at strong motion recording sites (Scasserra et al., 2008a). The emphasis was on both the classification of surface geology and average shear wave velocity in the upper 30 m of the site (Vs30). Each site has been assigned a Vs30 value along with an index pertaining to how the value was derived. Those indices are defined as:

- Category A: Velocity measured on-site using cross-hole, down-hole, or spectral analysis of surface wave methods;
- Category B: Velocity estimated based on nearby measurements on same geologic formation;
- Category C: Velocity estimated based on measurements from the same geologic unit as that present at the site (based on local geologic map);
- Category D: Velocity estimated based on general (non-local) correlation relationships between mean shear wave velocity and surface geology.

The database was then implemented in a newly developed web site with the purpose of disseminating the strong motion database and the source and site databank. That website is called SISMA, i.e. Site of Italian Strong Motion Accelerograms (http://sisma.dsg.uniroma1.it). The principal objective of the SISMA website is to provide high quality Italian strong motion records whose associated parameters are consistent and reliable and can be used for most engineering applications.

Another major application of the research was to evaluate the applicability of the most recent Ground Motion Predictions Equations (GMPE), developed in the Western United States (NGA2008) for shallow crustal earthquakes in tectonically active regions, to Italian data (http://peer.berkeley.edu/products/ngaproject.html). These GMPEs are intended to be applicable to geographically diverse regions, the only constraint being that the region is tectonically active and earthquakes occur in the shallow crust. The current practice in Italy has been a preference towards the use of local GMPEs derived solely from Italian data. The current national hazard map for Italy was developed using slightly modified versions of an Italian GMPEs (Sabetta and Pugliese, 1996), a European GMPE (Ambraseys et al., 1996), and GMPEs for particular regions within Italy (e.g., Malagnini and Montaldo, 2004). Because the NGA models represent a major advancement in GMPEs due to the quality and size of the database developed coupled with the relative sophistication of some of the functional forms, it was naturally of interest to determine if the NGA models could be applied in specific geographic regions such as Italy.

2.2 Regression models for estimating permanent displacements from seismic ground motion parameters

The research activity carried out in the third year by the R.U. of the University of Florence was mainly devoted to the definition of a number of empirical relationships that allow the assessment of permanent earthquake-induced displacement as a function of several related ground motion acceleration parameters. Permanent displacements were calculated by means of a numerical double integration procedure [Madiai, 2007] using a set of accelerometric signals derived from an Italian data base that has been developed at the Dipartimento di Ingegneria Strutturale e Geotecnica of La Sapienza, University of Rome [Lanzo, 2006].

A number of regression models were generated and compared with those obtained by some others Authors using different set of earthquake acceleration data. The proposed relationships allow to predict Newmark's sliding block displacement for 50% and 90% of confidence level, in term of: (1) critical acceleration ratio; (2) peak ground acceleration/squared peak ground velocity and critical acceleration ratio; (3) Arias intensity and critical acceleration ratio; (4) destructiveness potential factor and critical acceleration ratio; (5) fundamental period and critical acceleration ratio.

2.2.1 Selection of strong-motion database

The set of data used in the analyses for the definition of the empirical relationships consists of 196 free-field horizontal acceleration time histories from 46 Italian earthquakes in the magnitude range 4 to 6.3 recorded at 50 accelerometric stations with epicentral distance between 1 and 87 km.

Records were all exported from the web-database SISMA (Site of Italian Strong Motion Accelerograms) [Scasserra et al, 2008] in order to obtain an homogeneous set of data whose associated parameters are consistent and reliable.

According to the $V_{S,30}$ values in the subsoil underlying the accelerometric station, recordings on rock or rock-like soils (ground type A - $V_{S,30}$ > 800 m/s) were distinguished from those on stiff (ground type B - $V_{S,30}$ = 360÷800 m/s) and medium to soft (ground types C and D - $V_{S,30}$< 360 m/s) soils. The main statistics of the strong motion parameters used in the analyses are summarised in Table 1.

Table 1 - Main statistical parameters of the recording characteristics used in the analyses

		min	max	mean	mode	median	st. dev.
PGA	gal	30.75	397.53	124.33	127.48	97.08	80.22
PGV	cm/s	0.72	43.94	6.56	3.66	4.99	5.76
D_T	s	0.62	28.61	7.08	4.13	5.07	5.37
D_{BR}	s	3.60	51.68	16.39	14.57	13.75	10.14
I_a	cm/s	0.53	120.20	12.76	6.17	7.10	16.71
$n(D_T)$	1/s	2.61	41.99	12.50	18.21	10.51	6.91
$n(D_{BR})$	1/s	3.52	35.21	12.93	8.08	10.47	7.23
$P_D(D_T)$	$10^{-4}gs^3$	7.51E-03	1.26E+02	3.17E00	1.73E-01	5.27E-01	1.14E+01
$P_D(D_{BR})$	$10^{-4}gs^3$	7.75E-03	5.59E+01	2.25E00	1.15E-01	5.65E-01	5.93E00
$T_m(D_T)$	s	0.05	0.77	0.21	0.13	0.19	0.12
$T_m(D_{BR})$	s	0.06	0.57	0.21	0.20	0.19	0.11

In Table 1: PGA is the peak ground acceleration (or a_{max}); PGV the peak ground velocity (or v_{max}); D_T the Trifunac duration (from 5 to 95% Arias intensity); D_{BR} the bracketed duration (at 0.05 g); I_a Arias intensity; P_D the destructiveness potential factor (Araya e Saragoni, 1984); n the number of zero crossings; T_m the mean period (ratio between the duration and the half of the sum of the zero crossings).

2.2.2 Empirical relationships for assessing earthquake- induced displacements

Unsymmetrical displacement of Newmark's sliding block on a vibrating horizontal surface was calculated for each corrected signal of the selected set for a number of critical acceleration values, equal to 0.002, 0.005, 0.01, 0.02, 0.05, 0.1, 0.2g respectively. For each k_c value, two values of displacement were calculated, one for each of the two side of acceleration time history. The maximum of the two obtained values were assumed as displacement related to the signal.

Empirical relationships were developed adopting the ground motion parameters most commonly referenced: peak ground acceleration, peak ground velocity, Arias intensity, destructiveness potential factor, mean period. Various displacement functions were analysed considering the original form proposed by different Authors [Ambraseys e Menu, 1988; Whitman e Liao, 1984; Jibson, 1993; Crespellani *et al.*, 1998] and others modified forms in order to improve the correlation.

The performed study evidenced that influence of different type of subsoil (A, B, C+D soil class defined at §2.1) is negligible. Consequently, all the subsequent analyses were carried out regardless of the subsoil type underlying the monitoring accelerometric station.

The following equations were examined:

$$\log s = B_{1a} + A_{1a} \cdot \frac{a_c}{a_{max}} \qquad (s \text{ in cm}) \qquad (1a)$$

$$\log s = C_{1b} + B_{1b} \cdot \log \frac{a_c}{a_{\max}} + A_{1b} \cdot \log(1 - \frac{a_c}{a_{\max}}) \qquad (s \text{ in cm}) \qquad (1b)$$

$$s = A_{2a} \cdot \left(\frac{v_{mav}^2}{a_{max}} \right) \cdot e^{B_{2a} \cdot \frac{a_c}{a_{max}}} \qquad (2a)$$

$$s = A_{2b} \cdot \left(\frac{v_{max}^2}{a_{max}} \right) \cdot \left(1 - \frac{a_c}{a_{max}} \right)^{B_{2b}} \cdot \left(\frac{a_c}{a_{max}} \right)^{C_{2b}} \qquad (2b)$$

$$log\, s = C_{3a} + B_{3a} \cdot \frac{a_c}{g} + A_{3a} \cdot log\, I_a \qquad (s \text{ in cm, } I_a \text{ in m/s, } a_c \text{ in } g) \qquad (3a)$$

$$log\, s = C_{3b} + B_{3b} \cdot log \frac{a_c}{g} + A_{3b} \cdot log\, I_a \qquad (s \text{ in cm, } I_a \text{ in m/s, } a_c \text{ in } g) \qquad (3b)$$

$$log\, s = D_{3c} + C_{3c} \cdot \frac{a_c}{g} + (B_{3c} + A_{3c} \cdot \frac{a_c}{g})\, log\, I_a \qquad (s \text{ in cm, } I_a \text{ in m/s, } a_c \text{ in } g) \qquad (3c)$$

$$s = I_a \cdot 10^{B_{3d} + A_{3d} \cdot \frac{a_c}{a_{max}}} \qquad (s \text{ in cm, } I_a \text{ in cm/s}) \qquad (3d)$$

$$s = A_{3e} \cdot I_a \cdot \left(1 - \frac{a_c}{a_{\max}} \right)^{B_{3e}} \cdot \left(\frac{a_c}{a_{\max}} \right)^{C_{3e}} \qquad (s \text{ in cm, } I_a \text{ in cm/s}) \qquad (3e)$$

$$s = C_{4a} \cdot (P_D)^{B_{4a}} \cdot \left(\frac{a_c}{g} \right)^{A_{4a}} \qquad (s \text{ in cm, } P_D \text{ in } 10^{-4} \text{ g s}^3, a_c \text{ in } g) \qquad (4a)$$

$$s = P_D \cdot 10^{B_{4b} + A_{4b} \cdot \frac{a_c}{a_{\max}}} \qquad (s \text{ in cm, } P_D \text{ in } 10^{-4} \text{ g s}^3, a_c \text{ in } g) \qquad (4b)$$

$$s = A_{4c} \cdot P_D \cdot \left(1 - \frac{a_c}{a_{\max}} \right)^{B_{4c}} \cdot \left(\frac{a_c}{a_{\max}} \right)^{C_{4c}} \qquad (s \text{ in cm, } P_D \text{ in } 10^{-4} \text{ g s}^3, a_c \text{ in } g) \qquad (4c)$$

$$log \left(\frac{4s}{a_{max} T^2} \right) = A_{5a} - B_{5a} \cdot \left(\frac{a_c}{a_{max}} \right) \qquad (5a)$$

$$s = A_{5b} \cdot \frac{a_{max} \cdot T^2}{4} \cdot \left(1 - \frac{a_c}{a_{max}} \right)^{B_{5b}} \cdot \left(\frac{a_c}{a_{max}} \right)^{C_{5b}} \qquad (5b)$$

It can be notice that the equations in which the critical acceleration ratio (a_c/a_{max}) appears should predict displacement approaching infinity when a_c/a_{max}= 0 and approachin zero when a_c/a_{max}= 1. For this reason, in the present study an improvement of the various models was obtained by introducing into the regression the term $\left(1 - \frac{a_c}{a_{\max}} \right)^m \cdot \left(\frac{a_c}{a_{\max}} \right)^{-n}$.

The results of the regression analyses and the corresponding coefficient of determination, R^2, are summarised in Tables 2 to 7 for the equations 1a to 5b. The corresponding coefficients for a confidence level of 90% (assuming a lognormal distribution for the related variable at small probability of exceedance) and the results obtained by other Authors, for analogous relationships derived from sets of acceleration time histories collected from different worldwide earthquakes, are also shown in the same Tables for comparison.

Table 2 - Coefficients of the equations 1a and 1b

	A_{1a}	B_{1a}	R^2_{1a}	A_{1b}	B_{1b}	C_{1b}	R^2_{1b}
present study - c.l. 50%	-3.74	1.10	0.75	2.26	-0.86	-0.22	0.77
Ambraseys e Menu (1988)	-4.08	2.27	0.90	2.53	-1.09	0.90	0.93
Jibson (2007)	-	-	-	2.341	-1.438	0.215	0.84
present study - c.l. 90%	-3.74	1.76	-	2.26	-0.86	0.42	-

Table 3 - Coefficients of the equations 2a and 2b

	A_{2a}	B_{2a}	R^2_{2a}	A_{2b}	B_{2b}	C_{2b}	R^2_{2b}
present study - c.l. 50%	49	-8.5	0.94	3.89	2.57	-0.69	0.95
Whitman e Liao (1984)	37	-9.4	-	-	-	-	-
present study - c.l. 90%	95	-8.5	-	7.15	2.57	-0.69	

Table 4 - Coefficients of the equations 3a and 3b

	A_{3a}	B_{3a}	C_{3a}	R^2_{3a}	A_{3b}	B_{3b}	C_{3b}	R^2_{3b}
present study - c.l. 50%	1.37	-20.864	2.382	0.75	1.259	-1.502	-1.178	0.82
Jibson (1993)	1.46	-6.642	1.546	0.87	-	-	-	-
Jibson et al. (2000)	-	-	-	-	1.521	-1.999	-1.546	0.83
Jibson (2007)	-	-	-	-	2.401	-3.481	-3.230	0.71

Table 5 - Coefficients of the equations 3c, 3d and 3e

	A_{3c}	B_{3c}	C_{3c}	D_{3c}	A_{3d}	B_{3d}	R^2_{3d}	A_{3e}	B_{3e}	C_{3e}	R^2_{3e}
present study - c.l. 50%	13.13	1.07	13.88	2.17	-3.57	0.17	0.85	0.16	2.6	-0.60	0.84
present study - c.l. 90%	-	-	-	-	-3.57	0.63	-	0.47	2.6	-0.60	-

Table 6 - Coefficients of the equations 4a, 4b and 4c

	A_{4a}	B_{4a}	C_{4a}	R^2_{4a}	A_{4b}	B_{4b}	R^2_{4b}	A_{4c}	B_{4c}	C_{4c}	R^2_{3c}
present study - c.l. 50%	-1.406	0.777	0.006	0.791	-3.65	1.25	0.85	1.90	2.72	-0.60	0.85
Crespellani et al. (1998)	-1.338	0.977	0.011	0.841	-	-	-	-	-	-	-
present study - c.l. 90%	-	-	-	-	-3.65	1.72	-	5.51	2.72	-0.60	-

Table 7 - Coefficients of the equations 5a and 5b

	A_{5a}	B_{5a}	R^2_{5a}	A_{5b}	B_{5b}	C_{5b}	R^2_{5b}
present study - c.l. 50%	0.776	-3.136	0.86	0.978	2.554	-0.704	0.91
Cai e Bathurst (1996) - c.l. 50%	0.85	-3.91	-	-	-	-	-
present study - c.l. 90%	1.166	-3.136	-	1.340	2.554	-0.704	-
Ambraseys e Menu (1988) - upper bound	1.07	-3.83	-	-	-	-	-

2.3 GLE based multi-block model to evaluate slope seismic response

The occurrence of earthquake-induced landslides is documented in many post-earthquake damage reports. The experience of last decades showed that these phenomena represent one of the most damaging hazards associated with large earthquakes. Under seismic loading conditions, the assessment of earthquake-induced permanent displacements represents a suitable criterion for the evaluation of seismic slope response and post-seismic serviceability.

The sliding block model introduced by Newmark (1965) is directly applicable in cases of pure translational or rotational failures but can prove unrealistic in cases of mixed roto-translational failure mechanisms. Recently Sarma & Chlimintzas (2001) proposed a limit equilibrium multi-block model, for the evaluation of seismic and post-seismic slope displacements occurring along slip surfaces of general shape. In this model blocks slide under the condition that they do not separate or overlap with each others and with the slip surface, implying a rigid nature of the inter-block boundary. As the inter-block boundary remains unchanged in length and direction the component of displacements of two adjacent blocks normal to their boundary is the same for the two blocks. The displacement of all blocks can thus be expressed as functions of the displacement of a single block assumed as a reference through displacement conversion factors depending on the problem geometry. In this way the multi-block system is reduced to an equivalent single degree of freedom system. The equation of motion of the reference block coincides with that of a rigid block sliding on a horizontal plane, except for a shape factor S depending on slope geometry and soil strength parameters.

In order to satisfy kinematic compatibility of block displacements, during motion the mass of a block can be transferred into adjacent blocks. The transformation rules of the slope geometry were selected to meet the following criteria: i) each block keeps in contact with adjacent blocks and with the slip surface without separation or overlapping; ii) the total mass of the system is constant. If slope displacement is small in comparison with the length of the slope, the effect of mass-transfer is negligible and it can be assumed that each block slides as a rigid body along its slip surface segment without any mass-change. For large displacements the substantial change in the geometry of the soil mass during motion cannot be neglected. In fact, the geometrical rearrangement, tending towards a more stable configuration, is often the decisive factor that will eventually cause the slide to stop.

During the third year of the present Project, the R.U. of the University of Messina and Catania carried out the following main activities:

- implementation of the slope geometry rearrangement during motion in the GLE-based multi-block model;
- parametric analysis on simple slope schemes to evaluate the influence of soil mass rearrangement during motion on slope response;
- application of the GLE multi-block model for parametric analyses of landslides taking into account change in slope geometry and soil strength degradation.

In the proposed GLE method was used to detect the slope critical acceleration coefficient k_c. In the analysis, due to pore pressure build-up and change in slope geometry the weight $W_i(t)$ of the slices and pore water pressure $U_i(t)$ at the base of the slices are time dependent. $U_i(t)$ is the sum of the static pore pressure and of the seismic-induced excess pore pressure $\Delta u_i(t)$.
Saturated clay soils subjected to cyclic loading exhibit excess pore water pressures when the cyclic shear-strain $\gamma(t)$ is greater than the volumetric threshold γ_v. In the proposed procedure the time-history $\gamma_i(t)$ of the shear strain induced at the base of each slice of the slope was computed using an equivalent-linear approach.In the analysis small strain shear modulus $G_{0,i}$ was evaluated using the relationship by Rampello et al. (1994) and the modulus reduction curves proposed by Vucetic and Dobry (1991) for different values of the soil plasticity index I_P was utilised. For each of the computed shear strain time-histories ‘*significant straining cycles’* were selected detecting the cycles for which the mean cyclic amplitude $\gamma_{c,i}$ (obtained averaging the positive and negative peak values of the strain cycle) is greater than the volumetric threshold strain γ_v computed as a function of plasticity index I_P and over-consolidation ratio *OCR* (Matsui et al., 1980). The excess pore-water pressure ratio $\Delta u^*_{i,j}$ at the base of the i^{th} slice after the j^{th} significant straining cycle was evaluated as the product of the maximum excess pore pressure ratio and a weighting factor $\square_{i,j}$ derived assuming that the pore pressure build-up can be distributed over the number $N_{i,v}$ of significant cycles using Miner’s law of cumulative damage. The maximum value of excess pore pressure was evaluated according to Matsui et al. (1980). Once the time-history of the excess pore pressure is known for each slice of the slope, the current value $k_c(t)$ of the slope critical acceleration coefficient can be computed for each time step of the input accelerogram. Thus, $k_c(t)$ reduces from the initial value $k_{c,0}$, computed before the excess pore water pressure develops, to the minimum value $k_{c,min}$ attained when the maximum excess pore-water pressure is achieved in all the slices.

2.4 Coupled analyses to evaluate seismic slope displacements

The design procedures to evaluate earthquake-induced sliding displacements typically refer to three different approaches:

- - simplified methods;
- - displacement-based methods;
- - advanced dynamic methods.

In the first class of methods, empirical relationships are used to predict the permanent slope displacements (Bray & Rathje 1998). The second class includes simplified dynamic analysis, by means of the conventional Newmark rigid block model, as well as through its improvements to account for soil deformability (Kramer & Smith 1997, Rathje & Bray 1999, Ausilio et al. 2007a, 2008). The dynamic site response and the sliding block displacements are computed separately in the so called ‘decoupled’ approach, or simultaneously, in a ‘coupled’ analysis (e.g. ‘stick-slip’ model). The advanced dynamic methods are based on finite element (FEM) or finite difference (FDM) numerical solutions, which permit to account for topography and heterogeneity by two- or three-dimensional analyses.
The ‘seismic coefficient’ for conventional pseudo-static analyses can be deduced from the displacement-based methods, through the definition of ‘reduction factors’ of the maximum design surface acceleration (Stewart et al, 2003; Ausilio et al, 2007b). Three different types of reduction factors were defined in this work:

1) the ‘frequency reduction factor’, αF, as a function of soil deformability, expressed as the ratio of the fundamental subsoil period to the mean period of acceleration time history;
2) the ‘displacement reduction factor’, αU, expressed with reference to the ductility of a rigid sliding slope, corresponding to a limit value of the allowable displacement;

3) the ‘global reduction factor’, αFU, which considers simultaneously both the above features.

During the third years of the present Project, the R.U. of the University of Calabria carried out the following main activities:

- definition of the attenuation laws of ground motion parameters needed for the application of simplified relationships referring to Italian seismicity;
- implementation of a numerical model to perform the 1D coupled stick-slip analysis;
- comparison and validation of the proposed simplified relationships and the 1D stick-slip analyses with the displacements observed or computed using advanced 2D dynamic analyses for three different case histories.

2.4.1 Ground motion parameters and attenuation relationships for simplified methods

The simplified methods allow to predict the slope displacements through two stages:

1) estimate of the equivalent acceleration, a_{eq}, used to represent the seismic loading;
2) probabilistic evaluation of the displacement by means of simplified dynamic (Newmark) analysis.

Such calculation procedures need a preliminary estimate of ground motion parameters, such as significant duration and mean period of the design earthquake, which are not specified by either the national code or the seismic map. Therefore, an effort to estimate them statistically was made on the basis of the national seismic database. In a first approach, the seismic motion parameters (mean period and significant duration) have been considered like deterministic variables (Ausilio et al., 2007b). In an alternative approach, the statistic variability of the seismic motion parameters was accounted through attenuation laws suitable for the Italian seismicity. Reference was made to the attenuation laws by Kempton and Stewart (2006) and Rathje et al. (2004), for the significant duration and the mean period, respectively. The attenuation relationships have been re-calibrated on the basis of the database of Italian seismic records (SISMA, Scasserra et al. 2008). Acceleration time histories were selected with moment magnitude M_w between 4 and 7, for subsoil class A and without documented geo-morphological (site) effects.

The attenuation relationship for the significant duration is expressed as:

$$\log(D_{5-95}) = \log\left[-0.588 + 0.033 \cdot \exp\left(0.878 \cdot M_w\right) + 0.161 \cdot r_{jb}\right] + \sigma_D \cdot \varepsilon_D \tag{1}$$

where:

σ_D is the standard deviation (σ_D = 0.228);
ε_D is the standard error term of regression, distributed with a standard Gaussian law;
M_w is the moment magnitude;
r_{jb} is the distance of Joyner & Boore (1981).

The attenuation relationship for the mean period is expressed as:

$$\log(T_m) = -0.532 + 0.256 \cdot (M_w - 6) + 0.0033 \cdot r_{jb} + \sigma_T \cdot \varepsilon_T \tag{2}$$

where, again, σ_T is the standard deviation (σ_T= 0.155); ε_T is the standard error term of regression, distributed with a standard Gaussian law.

2.4.2 Coupled “stick-slip” analysis

A lumped-mass stick-slip model with generalized assumptions was implemented in a computer code (ACST) by Ausilio et al. (2008). The numerical solution can account for the compliance of the bedrock and the occurrence of a sliding surface at a generic depth, not necessarily coinciding with the bedrock. In no-slip condition (‘stick phase’), the equations of motion coincide with those of a (n+1)-degree of freedom system corresponding to the soil layering down to the bedrock. The sliding displacement is triggered when the inertia forces down to depth of the sliding surface (i.e. at the top of the s-th layer) are equal to the resistance corresponding to the product of the sliding mass and the yield acceleration. During the ‘slip phase’, the equations of motion are reduced to those of the (s-1) lumped mass system with the yielding shearing force at the base. The sliding displacements are finally computed integrating twice the sliding acceleration time histories, until the sliding velocity becomes zero.

The details of the numerical procedure are extensively reported by Ausilio et al. (2008); the preliminary application of the method appeared to confirm the conclusions by Rathje and Bray (2000), i.e. that the stick-slip method results conservative for soft soils and increasingly un-conservative for stiff soils, as the sliding depth increases.

2.5 Effect of soil stiffness on the seismic pseudo-static coefficient

Under seismic loading conditions the safety of an artificial or natural slope with respect to global instability phenomena depends on the maximum values of acceleration attained inside the slope body and, moreover, on the spatial distribution of instantaneous accelerations, that is to say, of inertial forces.

The development of asynchronous motions in slopes can be related to several factors, related to particular features of the input motion (frequency content, amplitude) and of the slope itself (geometry, stiffness of soils, etc.). In general, asynchronism tends to increase when the higher vibration modes of the system are excited. This condition should occur when the dominant frequencies of the seismic motion are relatively high and/or the natural frequencies of the dam low (slope very high or made of low stiffness soils).

As well known, under seismic loading conditions soil stiffness depends on the mobilized level of shear strain. This means that the severity of the input motion may strongly influence the development of asynchronism in slopes. Stronger earthquakes actually induce significant decrease in slope soil stiffness (with respect to the initial values), thus promoting the onset of asynchronism.

The asynchronism may be analysed experimentally or by theoretical predictions of the dam seismic response.

The experimental approach, even if valuable in highlighting the phenomenon, does not allow a complete characterization of it in the whole domain of interest because of the reduced number of measurement points. This means that the experimental data provide a very low spatial resolution, usually inadequate to observe the phenomenon in the whole slope. It should be further added that a seismic network frequently records seismic events of weak intensity and sometimes stronger ones. From a practical viewpoint, in slopes it is important analyzing asynchronism effects when strong earthquakes occur. In this case the issue of slope safety with respect to global instability becomes meaningful. For such additional reason, studying the phenomenon by a theoretical approach is almost unavoidable. Sophisticated mathematical-numerical models, available nowadays, assure reliable predictions of slope seismic response even to intense earthquakes.

The research activity carried out during the three years of the project was focused at studying the asynchronous motions in both natural and artificial slopes. The study involved both experimental and theoretical activities. Three main issues were developed during the research work:

a) Demonstrating experimentally the existence of asynchronous motion in slopes
b) Analyzing the asynchronous motion of natural slopes subject to strong earthquakes
c) Analysing the asynchronous motion of artificial slopes (earth dams) subject to strong earthquakes

With reference to points (b) and (c) the goal of the research activity was essentially that to investigate how the so called seismic coefficient (over a selected volume, the ratio between resultant of inertial forces and volume mass) is lower than the PGA/g ratio due to the activation of asynchronous motion and which factor affect mainly such reduction.

The issue of demonstrating experimentally the existence of asynchronous motion in slopes was carried out with regards to monitoring data observed on an Italian earth dam, the Camastra Dam (Italy). Records of accelerations detected on this dam before and during the research project were used to demonstrate experimentally the existence of asynchronous motion in slopes. Asynchronous motions in the dam embankment was detected by the temporal mismatch of the signals recorded at the dam top, mid-height and base.

The issue of analyzing the asynchronous motion in natural slopes consisted in investigating through a large number of dynamic linearly elastic analyses the influence of some key factors (slope height, slope inclination, Young's modulus, frequency content of the earthquake) on the asynchronous motions.

Asynchronous motions was investigated by calculating, for any volume V of the dam underlined by a potential slip surface S, the temporal evolution of the ratio khS(t) between the inertial forces induced by the earthquake, Fh,S(t), and the weight W of the volume V:

$$k_{hS}(t) = \frac{F_{hS}(t)}{W} = \frac{a_{hS,equiv}(t)}{g} \qquad (1)$$

where ahS,equiv(t) is the equivalent acceleration along the surface S and g the gravity acceleration.

The issue of analyzing the asynchronous motion in artificial slopes consisted in investigating through an advanced dynamic coupled approach the asynchronous motions of two selected earth dams.

Even in this case results were synthesized through the equivalent coefficient khS(t) referred to predefined potential slip surfaces.

The seismic response of the dams was investigated by 2D analyses, after discretizing the maximum cross-sections of the two embankments through the FE technique. The interaction between the solid skeleton and the pore fluid was modelled by a coupled dynamic approach based on the Biot generalized consolidation theory. The solid skeleton stress-strain response was simulated with the Hujeux constitutive model (Aubry at

al., 1982), which is an elasto-plastic combined-hardening model. It reproduces the essential features that soil exhibits under cyclic loads (non-linearity, non-reversibility, hysteresis, ratcheting, densification, cyclic mobility, liquefaction). The procedure was implemented in the code GEFDYN (Aubry & Modaressi 1996).
The seismic response of the Camastra Dam was evaluated considering seven different accelerograms, which seismological studies (Calvi 2004; Convertito and Herrero 2004) provided as representative of possible seismic scenarios expected at the dam site for different return periods, TR. These events were selected from the European Strong Ground Motion Database (Friuli Tolmezzo, 1976; Valnerina, 1979; Montenegro UH and PH, 1979) and the Japanese Kyoshin Network database (SZO002, 1997 ; KGS005, 1997; MYG010, 2003).
The seismic response of the El Infiernillo Dam was analysed for three earthquakes that actually occurred at the dam site. Two events correspond to the aforementioned earthquake of 14/03/1979 and 19/09/1985. The third one is a weak-motion event occurred on May 30, 1990. The event of 1979 (magnitude M= 7.6; epicentral distance d = 134 Km; PGA=0.1g) has a fundamental frequency around 2.5 Hz. The event of 1985 (magnitude M= 8.1; epicentral distance d = 68 Km; PGA=0.14g) has a fundamental frequency around 8 Hz. Finally, the event of 1990 (magnitude M= 5.5; epicentral distance d = 140 Km; PGA=0.02g) has a fundamental frequency around 10 Hz.
For the two selected dams the asynchronous motions were investigated by interpreting the results (essentially, the spatial distributions of total stresses and accelerations) obtained by the elasto-plastic FE analyses (Sica, Pagano, Modaressì, 2008; Sica & Pagano, 2009). Asynchronous motions was later investigated by comparing khS(t) obtained from equation (1) with the input acceleration (that can be intended as the overall embankment acceleration in the hypothesis of infinitely stiff soils) and to the accelerations computed in some points of V by the the elasto-plastic analyses.

2.6 Seismic response analysis of slopes with translational sliding mechanisms

The seismic performance of slopes can be evaluated in terms of permanent displacements of potentially sliding soil volumes. To this purpose, a decoupled approach can be used: firstly, a two-dimensional seismic response analysis of the slope is performed; then, displacements are evaluated by double integration of the acceleration time histories representative of the motion of the entire sliding mass relative to the base.
A parametric analysis was performed during second year of activity to define geometrical and mechanical features of idealised slopes; this research report discusses the results of two-dimensional seismic response analyses of these slopes, in which soil behaviour is described with a visco-elastic equivalent model. The input motions include six Italian seismic records all recorded on very stiff outcrop. Translational sliding mechanisms are studied using the decoupled approach, representing the motion of the sliding mass through the motion of its centre of gravity or trough equivalent acceleration time histories, which take implicitly into account the spatial variability of the acceleration within the sliding soil volume.
The computed displacements are related to the soil stiffness, to the size and location of the sliding mass within the slope, and to the properties of the seismic input, to support the prediction of earthquake-induced displacements for this category of sliding mechanisms.

In the domain analysed, in plane strain seismic response analyses, the ground surface has a constant inclination α of 10° or 20° and the large lateral extension of the domain was deemed necessary in order to reduce the effect of waves reflected from the right-hand vertical boundary.
Three volumes were selected with three different vertical distances from bedrock H = 15, 66 and 118 m; in each soil volume six potentially sliding surfaces were located, parallel to the ground surface, at depth D = 5, 10 and 15 m; the sliding surfaces had two length to depth ratio: L/D = 5 or 10. The overall lengths of sliding surfaces ranges from L = 25 to L = 150 m.
In the static pre-seismic condition two different profiles of the shear wave velocity V_s were assumed, in order to represent a medium-soft and a stiff clay deposit, these were obtained assuming a small-strain shear modulus G_0 depending on stress state and history. In the analysis, performed with the finite element method using the code QUAKE, an equivalent linear visco-elatic soil model was used, in which the laws for the decay of the secant shear modulus and for the increase of the damping ratio with increasing shear amplitude were taken from Vucetic & Dobry (1991) for a plasticity index IP = 25 %.

2.7 Analysis of seismic behaviour of natural slopes using Finite Element Method (FE) with advanced constitutive relations

Two different aims have been pursued:

- the ground response analysis of a horizontal soil deposit adopting numerical codes characterised by increasing level of complexity (*PLAXIS* and *SWANDYNE*). The results have been compared with those obtained using a one-dimensional visco-elastic linear equivalent approach (*EERA*) in order to define appropriate calibration procedures to be adopted for FE dynamic analyses based on simple constitutive hypotheses.
- the analysis of the seismic stability of an ideal slope using the code *SWANDYNE* and the advanced two-surface elasto-plastic constitutive model *MSS* (Kavvadas & Amorosi, 2000) able to predict some of the main features of the mechanical behaviour of soils when subjected to cyclic loading.

The results are briefly reported in the following section.

3 RESULTS

3.1 Updating of the Italian Database of Strong-Motion acclerograms and validation of new empirical attenuation laws for Italian territory

3.1.1 Main characteristics of the database of Italian strong-motion accelerograms

The database is composed of 247 Italian three-component corrected accelerograms from 101 recording sites and 89 earthquakes that occurred in the period 1972-2002 (Scasserra et al., 2008b).

The magnitude of the events is always available as local magnitude M_L. Moment magnitudes M_W are available for 60% of the earthquakes from moment tensor solutions. Surface wave magnitudes are also available for 36% of the events.

Re-calculated epicentral and hypocentral distances are available for all recordings. Joyner and Boore distances (r_{jb}), i.e. closest distance from the surface projection of the fault rupture, and closest distance from the rupture (r_{ru}) have been re-calculated only when fault solutions are available corresponding to about 45% of the recordings. About 85% of the records have been obtained at distances of less than 50 km from the source while the remaining 15% data are essentially concentrated at distances between 50 and 100 km.

Site classification was based on the equivalent value for the shear-wave velocity over the uppermost 30 m, according to EC8 classification system. It has been possible to classify slightly less than 50% of stations from measured shear wave velocity profile, inferred from literature data or measured in-situ by ad hoc SASW investigations, whereas for the remaining stations V_{s30} parameter has been estimated based on correlations with surface geology.

Fault rupture classification has been obtained for slightly less than 70% of the earthquakes in the databank. Records from normal rupture mechanism dominate, about 40 earthquakes belonging to this category; remaining events are related to strike-slip (7), oblique (4) and thrust (10) ruptures.

3.1.2 The “SISMA” web site

The SISMA website was designed to be a user-friendly system intended to provide freely downloadable strong motion data and metadata for engineering applications (Scasserra et al., 2008c).

The design of SISMA allows records to be located in several ways, depending upon a user’s interest. Three different search criteria can be employed, i.e. “Search Eqk”, “Search Station” and “Search Recording” by using the respective buttons on the SISMA front page. The searchable earthquake parameters are earthquake name and year of occurrence, region, fault mechanism, local magnitude and focal depth. Local magnitude has been preferred to other magnitude definitions as search criterion because it is available for all the earthquakes included in the database. The searchable station parameters are station name and region, instrument type and housing, agency, and site classification according to EC8 or V_{s30}. In the “Search recording” window, the search parameters can be a combination of earthquake, fault mechanism, distance, site classification and ground motion parameters. SISMA offers a large number of searchable strong motion parameters such as peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), significant duration, Arias intensity (I_a), mean period (T_m), predominant periods (T_p), spectral acceleration at T=1s and Housner intensity (I_H). An additional feature of SISMA is the capability of displaying interactive maps of epicenter locations of seismic events recorded by a selected station which makes use of the GoogleEarth web service. A recent feature is the possibility of downloading multiple selected recordings.

3.1.3 Comparison of Italian accelerometric data with NGA2008 attenuation relations

As already said, ground motion prediction equations (GMPEs) have recently been developed in NGA project that are intended for application to shallow crustal earthquakes in tectonically active regions. It has been investigated the compatibility of those models with respect to magnitude-, distance-, and site-scaling implied by Italian strong motion data. This is of interest because (1) the Italian data is principally from earthquakes in extensional regions that are poorly represented in the NGA dataset and (2) past practice in Italy has been to use local GMPEs based on limited data sets which cannot resolve many source, path, and site effects known to be significant. It was found that the magnitude scaling implied by the Italian data is compatible with the NGA relations. However, the Italian data attenuate faster than implied by the NGA GMPEs at short periods, and the differences are statistically significant for three of four NGA relations used. Three regression coefficients are re-evaluated for the three affected NGA GMPEs to reflect the faster attenuation; a constant term, a geometric spreading and anelastic attenuation term, and a source depth term. The scaling of ground motion with respect to site shear wave velocity is consistent between the NGA models and Italian data. Moreover, the presence of nonlinearity in the Italian data is confirmed and found to be generally compatible with what is provided by NGA site terms. On the basis of these findings, it is recommended that NGA relations, with the aforementioned minor modifications, be used to evaluate median ground motions for seismic hazard analysis in Italy (Scasserra et al., 2008d).

3.2 Regression models for estimating permanent displacements from seismic ground motion parameters

A number of empirical relationships are derived that allow the assessment of permanent Newmark's sliding block displacement for 50% and 90% of confidence level, in term of several ground motion acceleration parameters. The formulated regression models were compared with the correlations obtained by some others Authors using different set of earthquake acceleration data.

The performed analyses indicate that the introduction of the critical acceleration ratio (a_c/a_{max}) improves the correlations between the permanent displacement and the related ground motion acceleration parameters. With the only exception of the simple regression between Newmark's sliding block displacement and critical acceleration ratio, it was observed that the proposed relationships exhibit high values of the coefficient of determination even if the calculated displacements fall in a large band for a range of significant displacements from an engineering point of view. Moreover, since the set of signals was derived from earthquakes occurred in a limited time (the first available instrumental data from the seismic Italian network date back to 1972), the considered parameters vary in a rather limited range. On the other hand, given the great uncertainty generally associated with the definition of empirical relationships, their use will be made with great caution. Therefore, the regressions proposed are not recommended for use in site-specific design, but a preliminary estimates of the expected coseismic displacements for slopes can be obtained from the proposed equations with a sufficiently good degree of confidence.

3.3 GLE based multi-block model to evaluate slope seismic response

3.3.1 Effect of excess pore pressure and mass transfer

The proposed GLE-based multi-block model was applied to parametric studies of several ideals slope scheme and different landslides reactivated by the Irpinia-earthquake of November 23, 1980 (M = 6.9). Herein only the analyses relevant to the case of the Calitri landslide are synthetically reported. Details on the geometrical and geotechnical features of the Calitri landslide are reported by Hutchinson and Del Prete (1985) and Martino & Scarascia Mugnozza (2005). The landslide developed across two sedimentary sequences: the 'Ariano' and the 'Atessa' formations, with an interposed deep deposit of scaly clays. Hutchinson and Del Prete (1985) refer of displacements of about 1-2 m close to the crest of the slope and of about 0.8 m in the city centre, observed immediately after the earthquake.

A parametric analysis was carried out varying the residual friction angle along the slip surface. In particular three cases were considered in which the residual friction angle of the 'Ariano' silty clays was assumed equal to 15.5° (case 1), 16.5° (case 2) and 18° (case 3); for the scaly clays the residual friction angle is assumed equal to 11° (mean value of the literature range). In dynamic analyses the landslide was discretized in 9 blocks and the block n.2 was assumed as reference block. The component of the acceleration record in the NS direction (a_{max} = 0.176g), roughly corresponding to the main movement direction, was adopted as input motion.

For the three cases considered in the analysis the initial value of the slope critical acceleration coefficient $k_{c,0}$ varies in the range 0.007-0.025. For each case, the maximum values of the excess pore pressure ratio □u^* evaluated at the end of the input motion vary along the failure surface. In particular □u^* is equal to zero close to the crest of the slope and increases in the central part of the slip surface assuming values in the range 0.3-0.35 in the 'Ariano' deposits and 0.1-0.2 in the scaly clays; near the toe of the slope Δu^* is of about 0.7.

For each case three displacement analyses were performed. In the first analysis (Analysis 1) the displacements of the blocks were evaluated neglecting excess pore pressures and mass transfer, therefore assuming a constant value of the critical acceleration coefficient. In the second analysis (Analysis 2) displacements were evaluated considering the change of the critical acceleration coefficient due to the excess pore pressure build-up but the mass transfer effect was neglected. In the last analysis (Analysis 3) both effects were considered.

The results of the three analyses are examined in terms of time history of k_c and displacement of the reference block. In cases 1 and 2 the excess pore pressure (Analysis 2) reduces the initial critical acceleration coefficient to negative, and then unrealistic, values; as a consequence block displacements diverge. If the effect of slope geometry change is considered (Analysis 3) the values of k_c at the end of the input motion are, in all cases, positive and then the displacements of each block are finite, but much larger than those observed after the landslides. In case 3 the displacement of the reference block evaluated in the Analysis 3, including pore pressure build-up and change in slope geometry, is of about 1.5 m. The vertical component of the displacement of all blocks of the system, obtained in Case 3 - Analysis 3 are in a good agreement with those reported by Hutchinson & Del Prete (1985).

3.4 Coupled analyses to evaluate seismic slope displacements

The three different approaches for evaluation of seismic displacements were applied to well-documented case studies available in literature. These cases were selected since meaningful displacements were observed during strong-motion earthquakes, and because the seismic actions and the geotechnical properties were sufficiently known.

In particular, the simplified relationships were applied to the case history of the rotational sliding of Calitri, reactivated by the Irpinia earthquake of November 23, 1980 (M = 6.9) with incremental displacements observed as high as 2.0 m (Tropeano et al., 2008; Ausilio et al. 2009). The predictions of the simplified relationships were compared with the results of the coupled stick-slip model developed by this R.U. (ACST, Ausilio et al. 2008), of a FDM commercial code FLAC 5.0 (Itasca 2005) and with the observed displacements.

The various methods were also compared for the cases of two earth dams (Tropeano et al. 2008) that presented displacements during the Loma Prieta earthquake (1989, M = 7.0) (Harder et al. 1998).

In all cases, the prediction resulted compatible with the observed displacements.

3.5 Effect of soil stiffness on the seismic pseudo-static coefficient

Results connected with the activities of demonstrating experimentally the existence of asynchronous motion in slopes showed that during the Molise earthquake (October 2002) the three signals reordered on the dam body resulted almost synchronous, while during the Appennino Lucano earthquake (September 2006) they often are in opposition. The different observed behaviour was interpreted by estimating the wavelengths associated to the seismic wave propagation in occasion of the two selected earthquakes (Sica, Pagano, Vinale, 2008). The wavelengths were estimated on the basis of the fundamental frequencies characterizing the input motion and of the shear wave velocity measured in the dam soils by in-situ tests (Pagano, Mancuso, Sica, 2008). The dominant wavelength was estimated to be over 100 m in the case of the Molise earthquake and of about 40 m in the case of the Appennino Lucano earthquake. By comparing the computed wavelengths to the dam height (H=57m), it clearly emerges why asynchronism was more pronounced for the second event.

Results connected with the activities of analyzing the asynchronous motion in natural slopes were synthesized in charts where the coefficient k_{hS} (defined as maximum value of the computed function $k_{hS(t)}$) is plotted against the Young's modulus. Such charts indicate that whatever the geometry assumed for the slope scheme and for the potential slip surface the values assumed by k_{hS} are significantly less than the PGA/g value, at least in the range of Young's modulus values of interest for soils.

The same plots also indicate that k_{hS} reduces with increasing the slope height and the depth of the potential slip surface and with decreasing the soil Young's. Consistently with experimental results obtained at the Camastra Dam, results also indicate that the higher the frequency content of the acceleration signal, the more pronounced the asynchronous is and, consequently, the lower the coefficient k_{hS} is.

Results connected with the activities of analyzing the asynchronous motion in artificial slopes have been represented plotting the equivalent accelerations $a_{hS,equiv(t)}$/PGA computed in the two dams for all possible surfaces and seismic events towards the maximum depth of the surface and its linear extension.

From these plots this broad conclusion can be drawn: the equivalent acceleration decreases more than linearly with the two selected geometrical variables.
Plots of all computed seismic coefficients $k_{h(Si)}$ against the PGA of the input motion show that k_h increases with the PGA of the input motion but with a decreasing derivative. This behaviour could be attributed to the plastic mechanisms taking place in the dam embankment when stronger earthquakes occur.
Results also how that the dam height has proven to be a key factor in promoting the onset of asynchronous motions and the consequent reduction of the equivalent seismic coefficients.

3.6 Seismic response analysis of slopes with translational sliding mechanisms

The results allowed to relate the seismic performance of these slopes to a number of factors, including the size of the potential sliding volume, its position within the slope, the stiffness of the soil deposit, and the frequency content of the input record.
While all these factors contribute to the seismic performance of the slope, it was possible to isolate the quantity that mainly controls the permanent displacements as the ratio of the estimated wavelength to the size of the sliding soil volume. As this factor increases, the instantaneous inertial forces tend to balance out, and the net inertial effect on the selected soil volume decreases.
However, this quantity cannot take into account amplification phenomena that are produced by the seismic response of the entire slope. For the idealised slopes studied in this paper, the predominant frequency of the different seismic inputs was usually larger than the fundamental frequency of the soil deposits, evaluated in the hypothesis of 1D wave propagation. Therefore, in most cases amplification can be ascribed to two-dimensional effects, consisting in the combination of waves arriving at a specific location after multiple reflection on the top and bottom boundary of the analysis domain. This interpretation is consistent with the finding that the seismic effects obtained for the soil volumes located uphill (H = 120 m) are generally more important than those of the corresponding soil volumes located downhill (H = 15 m).

A comparison between the displacements evaluated using the accelerograms computed, at the centre of gravity of the sliding masses, and those obtained using the equivalent accelerograms was done. Generally using the accelerogram in a fixed point of the sliding mass, such as the centre of gravity, may be somewhat misleading.
When using the accelerograms computed at the centre of gravity of the sliding masses, we account only for the amplification effects, but we also assume that the seismic motion in the centre of gravity is uniform throughout the sliding mass. Instead, when using the equivalent accelerograms, more consistently, the asynchronous motion of single soil particles can be deemed and smaller displacements are obtained for the longer surfaces.
It can be seen that for the soft soil, the use of equivalent accelerograms globally results in displacements lower than those computed using the input accelerograms. For the stiff soil, unrealistic amplification of displacements can be evaluated when using the accelerograms at the centre of gravity, irrespective of the depth of the sliding surface. Viceversa, when the equivalent accelerograms are used, larger displacements than the ones computed using the input accelerogram can be obtained only for shallow and short sliding mechanisms, that is for small volumes of the sliding mass.

3.7 Analysis of seismic behaviour of natural slopes using Finite Element Method (FE) with advanced constitutive relations

3.7.1 Ground response analysis

The one-dimensional propagation of 4 different earthquakes through a 60, 120 and 240 m thick homogeneous horizontal clayey layer has been studied, under comparable conditions, using the following different numerical codes:

- *EERA* (Bardet *et al.*, 2000): 1D equivalent visco-elastic approach;
- *PLAXIS* (2003) and *SWANDYNE* (Chan, 1995): 2D finite element dynamic analysis in terms of effective stress using a visco-elastic constitutive model with Rayleigh viscous damping.

A soft clay deposit was assumed in the analyses. Typical profiles of initial shear modulus G_0 with depth have been adopted. The curves of G/G_0 and damping D with shear strain have been evaluated using the indications proposed in the literature, as function of the plasticity index.
A parametric study has been performed in order to highlight the role of different geometries and boundary conditions on the results, expressed in terms of Fourier and Response spectra at different depths, assuming as a reference the *EERA* corresponding outcomes.

The damping profile with depth obtained with *EERA* has also been assumed as a reference for the calibration of the Rayleigh damping parameters in the FE dynamic analyses performed with *PLAXIS* and *SWANDYNE*. A novel calibration procedure for the stiffness and damping parameters has been proposed, leading to satisfactory matching between the FE analyses and the *EERA* ones.

3.7.2 Advanced dynamic analyses

The problem studied with the FE advanced analyses is represented by an ideal slope, made of clay, with $\beta = 20°$ and H=20 m. Two different soil characteristics were assumed: one set of analyses was carried out on an ideal soft clay, while the other was performed on a slope made out of stiff overconsolidated clayey soil. A parametric study has been carried out to evaluate the influence on the results of the material overconsolidation, the depth of the bedrock, the maximum acceleration of the seismic action and the geometry of the mesh on the results. The mechanical behaviour of the soil has been simulated with the advanced multi-surface *MSS* model, with suitable values of model parameters.
In order to obtain realistic results from the dynamic simulations, a simplified geological history of the slope has been simulated through appropriate static analyses before the application of the seismic action at the bedrock level. Two columns of viscous elements have been adopted along the vertical boundaries of the mesh in order to minimize the problem of wave reflection during seismic action.
The seismic behaviour of the slope has been studied applying at the bottom of the mesh the horizontal component of the accelerogram recorded at Loma Prieta (USA) during the earthquake of 1989.
As the hysteretic dissipation provided by the constitutive model is close to zero for low amplitude cycles, a small amount (≈ 2%) of Rayleigh damping has been added in all the FE simulations.

The main advantages of such sophisticated dynamic analyses of the slope are represented by the possibility of: i) describing in a relatively accurate way the stiffness decay with shear strain and the related hysteretic damping provided by the soil; ii) limiting the amount of the fictitious viscous damping to be added during the analysis to a small value (1÷2 %); iii) predicting the plastic strain accumulation and excess pore pressure built up during the earthquake within the domain; iv) describing the evolution of the state of the soil due to the dissipation of the excess pore water pressures after the end of the seismic action.

4 CONFORMITY TO THE PROGRAM

The research activities of Linea 6.3 were carried out in accordance with the scheduled program.

The activities planned for the last year of the project concerned a parametric study for evaluating the influence of slope deformability in the seismic performance of ideal slopes representative, for geometrical conditions and mechanical parameters, of the scenarios often encountered in applications. Both planar and rotational failure mechanisms were considered in the analyses referring to the scheme of infinite slope and of slopes of limited height.

For a selected number of the schemes mentioned above, advanced numerical analyses were carried out to validate the capability of simplified procedure in predicting the behaviour of ideal slopes under seismic conditions.

Back analyses of documented case histories were finally carried out using both simplified and advanced procedures for validating the predicting capability of methods of analysis of increasing complexity against observed behaviour.

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