30 Mar 2001, 10:30 am - 12:30 pm

Effects of Vertical Seismic Accelerations on Slope Displacements

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ABSTRACT

The behaviour of earth slopes under seismic conditions can be effectively studied by evaluating the suffered displacements, which are key parameters in the recent performance design approaches (Pianc/PTCII/WG34, 2001). Different methodologies have been developed to evaluate displacements (Whitman, 1993). Slope instabilities caused by yielding due to seismic inertial forces can be studied by methods based on the well-known model of a rigid block sliding on a plane surface (Newmark 1965). These methodologies utilise accelerometric time histories which allow to take into account the real characteristics of the seismic motion (Simonelli and Viggiani 1995). Displacement analyses are traditionally performed adopting only horizontal accelerograms. The aim of this paper is to evaluate the effects of vertical components of seismic motions. In this case, the critical acceleration depends on the direction of the resulting motion (Sarma 1975, 1999). The analyses have been performed for three major Italian earthquakes. The case of an indefinite slope in dry cohesionless soil has been examined. The results of the analyses have been synthesised in diagrams, which show that the displacement variations induced by vertical accelerations are negligible for the range of displacements values (of the order of centimetres), which are of interest from an engineering point of view.

INTRODUCTION

Accordingly to most national and international codes, the study of the behaviour of slopes and earth structures is performed by pseudo-static methods. These methods consider the dynamic inertia forces induced by the seismic accelerations as static actions, proportional to the soil mass by conventional seismic coefficient. The values of such coefficients are determined on the basis of the expected seismic accelerations, and sometimes on the probability of occurrence of the design earthquake. In most cases the design only requires to account for horizontal seismic actions, assuming that the effect of vertical accelerations is negligible.

A more effective and even simple analysis, can be performed utilising Newmark derived methods (Whitman, 1993), which are based on the classical model of a rigid block sliding on a plane surface subjected to a accelerometric time-history (Newmark, 1965). The block is subjected to an inertia force which depends on the real accelerations, and varies with time accordingly to the design time-history (see the scheme for a slope in Fig. 1).

For any particular configuration of the examined "soil structure" system a critical acceleration can be determined (by means of a pseudo-static analysis) beyond which the input accelerations produce a relative movement between the "structure" (e.g. the slope or a retaining wall) and the "base", and a final permanent displacement occurs at the end of the exciting time-history.

Many studies have been conducted on the behaviour of slopes under seismic actions, by means of Newmark derived models. Critical accelerations have been determined for different soil conditions, taking into account even the presence of vertical input motion, or the build-up of pore pressure for saturated soils in undrained conditions (Sarma, 1975 and 1999).
Extensive applications of such "displacement methods" have been performed, to account for different kinds of real earthquake accelerograms and for the probability of exceedance of assigned displacements (e.g. Ambraseys and Menu, 1988). In some cases, regional design charts have been drawn, on the basis of selected sets of accelerometric time-histories (e.g. Simonelli and Fortunato, 1996; Simonelli, 1997).

As a matter of fact these methods, even implementing a relatively simple model, provide reliable results which account for real accelerometric data, available today all over the world.
Further, such methods which do not evaluate limit equilibrium conditions, but investigate the behaviour of the "structure" in terms of induced displacements, are being widely used in most recent "performance based design" approaches (see PIANC/PTCII/WG34, 2001).

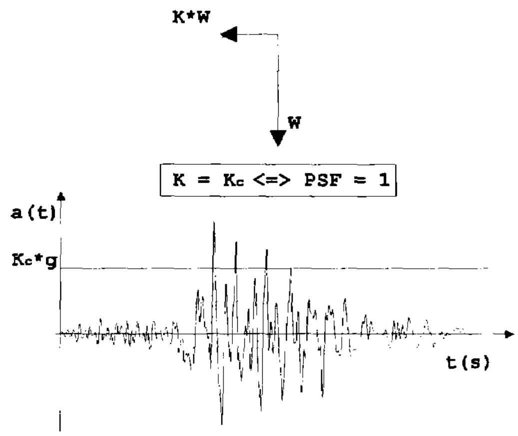


Fig. 1. Slope under seismic actions: critical acceleration concept.

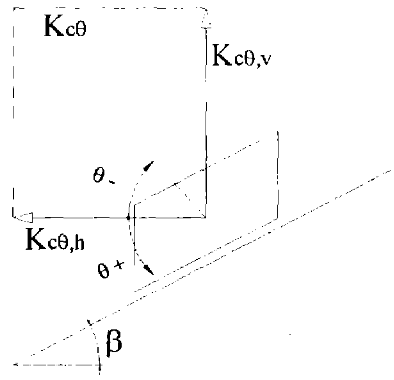


Fig. 2. Critical acceleration coefficient along θ direction ($K_{c\theta}$), and its components along horizontal ($K_{c\theta,h}$) and vertical ($K_{c\theta,v}$) directions.

In the present study, a Newmark-derived model for slopes is implemented, which accounts for both horizontal (a_h) and vertical (a_v) input motions, with the aim to investigate on the influence of vertical accelerations on suffered displacements.
As a matter of fact, in some earthquakes significant accelerations were recorded (a_v~$0.8\div1.0 \cdot a_h$), causing severe damage on structural systems.
The analyses will be performed utilising real accelerometric data, recorded during some major Italian earthquakes.

ANALYSIS MODEL

In the classic analysis of the behaviour of slopes by means of the Newmark model, the unstable soil mass is represented by the sliding block, and the soil underneath is the inclined plane subjected to the horizontal accelerometric time-history. The block and the plane move together, up to a threshold acceleration ($K_c \cdot g$) whose induced inertia force causes the limit equilibrium condition. As the exciting acceleration overcomes the critical one, the block slides over the plane.

The relative displacement *u* between the block and the plane is obtained by the double integration of the equation:

$$\ddot{u} = [g \cdot \cos(\beta-\varphi) / \cos\varphi] \cdot [K(t) - K_c] \qquad (1)$$

where β is the slope angle, φ is the soil friction angle, $K(t) \cdot g$ is the exciting accelerogram and K_c is the critical acceleration coefficient.

In this study the input motion is given by the sum of the horizontal and vertical components of real accelerograms.
Hence the resulting acceleration has a generic direction θ, along which a proper value of the critical acceleration $K_{c\theta}$ must be evaluated (see Fig. 2).
General expressions for K_c have been proposed by Sarma (1979 and 1999) by the analysis of the limit equilibrium condition for complex soil configurations. In the simple case of dry cohesionless soil, the critical acceleration coefficient is:

$$K_{c\theta} = \frac{\sin\beta\,(\tan\varphi \;/\; \tan\beta - 1)}{\cos(\beta-\theta)\;\;[1 + \tan\varphi \cdot \tan(\beta-\theta)]} \qquad (2)$$

and equation (1) modifies as follows:

$$\ddot{u} = \{g \cdot \cos[\beta-\theta(t)-\varphi] / \cos\varphi\} \cdot [K(t) - K_{c\theta}(t)] \qquad (3)$$

The critical acceleration coefficient $K_{c\theta}$ versus the acceleration direction θ is plotted in Fig. 3 for (φ -β)=5° (θ is positive when the vertical acceleration component is directed downward). The curve is not symmetric with respect to θ=0 axis, and the minimum value for K_c is obtained for θ slightly lower than zero. Hence the horizontal critical coefficient, K_{ch}, is about the minimum, and as θ increases or decreases, $K_{c\theta}$ increases rapidly assuming values much higher than K_{ch}.

In order to better forecast the role of vertical accelerations, in Fig. 4 the ratio between the horizontal component of $K_{c\theta}$ and the horizontal critical acceleration K_{ch} is plotted versus the direction θ, for different values of the difference (φ-β). The figure shows that when the vertical acceleration of the block is directed downward (θ > 0), the horizontal component of the critical acceleration $K_{c\theta}$ is higher than K_{ch}, hence improving the safety against potential sliding. If the block vertical acceleration is directed upward (θ < 0), the horizontal component of $K_{c\theta}$ is only

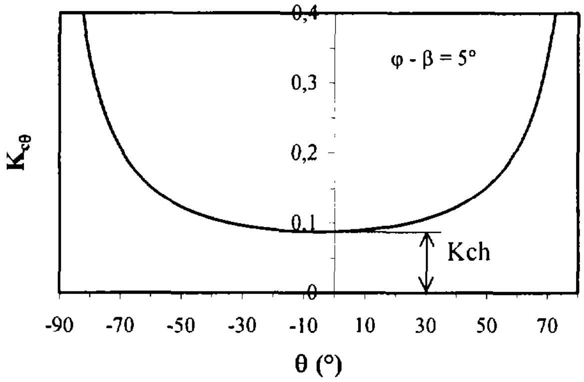


Fig. 3. Critical acceleration coefficient $K_{c\theta}$ versus direction θ (for φ - β = 5°).

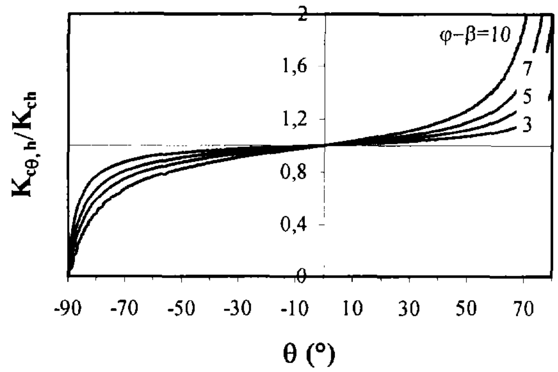


Fig. 4. Ratio between the horizontal component ($K_{c\theta,h}$) of the critical acceleration coefficient ($K_{c\theta}$) versus direction θ, for different values of mechanical and geometrical characteristics of the slope.

slightly lower than K_{ch}. Hence, it is clear that the vertical acceleration can be effective for sliding only if even a significant horizontal component simultaneously occurs. As an extreme consequence, according to the described model, in the case of vertical accelerograms having no peaks in phase with the peaks of the horizontal motion, the seismic response of the slope is not affected at all.
Hence, in order to correctly investigate on the effectiveness of real vertical accelerations, in the following analyses a wide set of recorded accelerometric data relative to different Italian earthquakes will be utilised, taking into account various combinations of accelerometric waveform characteristics (peak acceleration and velocity values, frequency, phase, duration).

REFERENCE EARTHQUAKES

The accelerometric data chosen for the analyses are relative to three major Italian earthquakes: Friuli 1976, Irpinia 1980 and Umbria-Marche 1997.

Most data, recorded by analogue accelerometres, consisted of three components (along WE and NS horizontal directions and DU vertical direction), and of the instrumentation noise time-history. All the data have been corrected in the frequency domain, in order to eliminate both the low and the high frequency noise effects, mainly due to the recording equipment (Simonelli and Viggiani, 1995).

The three reference earthquakes occurred with different features. Friuli event was characterised by a deep source (9-16 km), short duration (about 10 s), high values of maximum accelerations, high frequency content (up to 5 Hz). Irpinia event was characterised by deeper source (10-18 km), long duration (about 80 s), smaller values of maximum accelerations, low predominant frequencies (1-3 Hz). Umbria-Marche event was characterised by shallow source (7-8 km), short duration, high values of maximum accelerations and high predominant frequencies; here the maximum values of the ratio between the energy content of the vertical and the horizontal ground motions were computed.

The main characteristics of three typical accelerograms recorded at Tolmezzo (Friuli), Calitri (Irpinia) and Colfiorito (Umbria) are summarised in Table I. The main horizontal component and the vertical one are shown in Fig. 5.
The comparison shows that the higher accelerations (0.3-0.4 · g) were recorded at Tolmezzo and Colfiorito, while at Calitri they were much lower (<0.2·g). Nevertheless, the energy of Calitri seismic motion was much higher (see Arias intensity I_A up to 140 cm/s) than those measured at Friuli and Umbria sites.

EARTHQUAKE	Comp.	D (s)	Amax (g)	V max (cm/s)	Ia (cm/s)	Fo (Hz)
TOLMEZZO	NS	36	0,367	19,19	81,23	2,00
06/5/1976	WE	36	0,319	19,10	122,21	1,50
20 00' 13"	DU	36	0,263	9,13	33,04	7,60
CALITRI	NS	86	0,154	24,77	105,87	1,11
23/11/1980	WE	86	0,180	26,41	137,21	1,02
18 34' 52"	DU	86	0,160	17,74	79,32	1,00
COLFIORITO	NS	41	0,322	9,69	46,44	3,30
26/09/1997	WE	41	0,236	10,68	35,90	2,87
00 33' 16"	DU	41	0,219	7,76	29,09	2,37

Tab. 1. Main features of three typical accelerograms of Friuli 1976 (Tolmezzo), Irpinia 1980 (Calitri) and Umbria-Marche 1997 (Colfiorito) earthquakes.

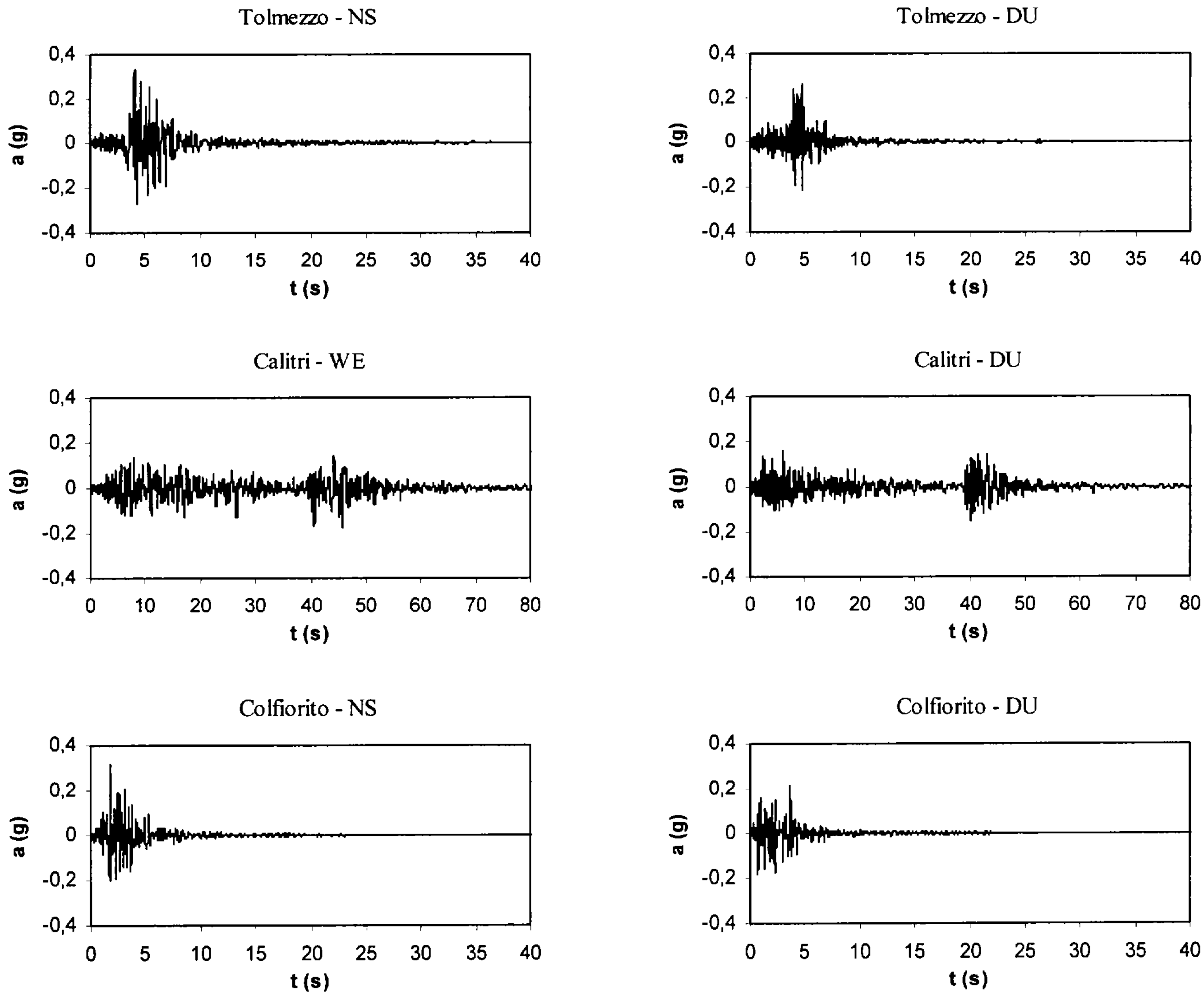


Fig. 5. Main horizontal (NS, WE) and vertical (DU) accelerograms recorded at Tolmezzo (Friuli 1976), Calitri (Irpinia 1980) and Colfiorito (Umbria-Marche 1997).

This was due to both the higher duration (d) of the motion (d >80 s in Irpinia, d~40 s in Friuli and Umbria) and the lower frequency content (see predominant frequency Fo~1 Hz at Calitri, Fo~2-3 Hz for Friuli and Umbria recordings). The values of Arias intensitiy and maximum velocity in Table I confirm that higher ratios between the vertical and the horizontal energy contents were recorded at Umbria sites.

ANALYSES AND RESULTS

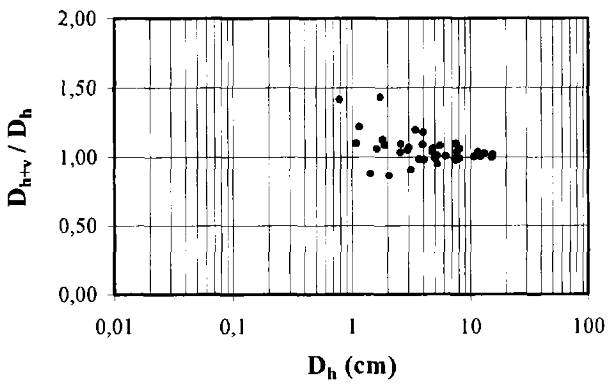
The evaluation of the effects of the vertical accelerations has been investigated, adopting the model previously described, and assuming as input motion the accelerometric recordings relative to the earthquakes illustrated in the previous paragraph.

The simple case of an indefinite slope in dry cohesionless soils has been studied, nevertheless the results of the analyses can be considered meaningful even for more complex geometrical and geotechnical configurations. The actual accelerograms have not been scaled, since in the Authors' opinion the scaling of amplitude should imply a proper modification of frequency and time duration of the waveform. The displacements have been computed for different values of friction angle φ and slope angle β (i.e. of critical acceleration coefficient $K_{c\theta}$).

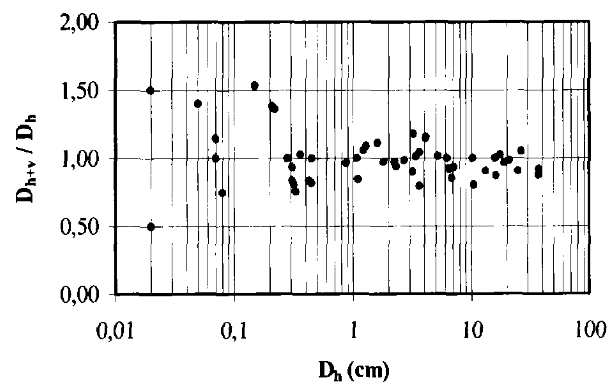
In particular, for any accelerogram the displacement induced by each of the horizontal components (D_h) and by the horizontal plus the vertical component (D_{h+v}) have been computed. Each horizontal component has been utilised twice, considering as effective one of the two opposite directions at a time.

The results have been analysed separately for the three regions. Obviously the displacements vary in a wide range, accordingly to the ratio between the input and the critical accelerations.

FRIULI



IRPINIA



UMBRIA - MARCHE

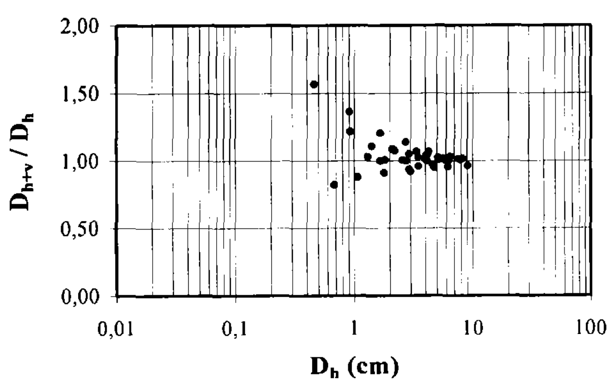


Fig. 6. Effect of vertical accelerations on permanent displacements: ratio between displacement induced by horizontal plus vertical seismic motion (D_{h+v}) and displacement induced by horizontal accelerogram only (D_h), versus D_h.

In order to investigate the effect of vertical input motion on permanent displacement, the ratio between the displacement induced by both horizontal and vertical components (D_{h+v}) and the displacement induced by the correspondent horizontal component only (D_h) has been plotted against the latter (D_h).

The results for the three regions are drawn in Fig. 6. Even if the diagrams are slightly different for the three cases, some main observations can de outlined:

1. the ratio (D_{h+v} / D_h) assumes both positive and negative values, clearly evidentiating that the vertical motion can even produce a reduction of the displacement, compared to the one induced by the horizontal component only;
2. the ratio (D_{h+v} / D_h) varies in a wide range (up to ~ 0.5-1.5) for very small values of displacement induced by horizontal component only (D_h up to ~ 1 cm);
3. the ratio strongly decays with increasing D_h,, and stays below 1.1 for displacement D_h greater than about 10 cm.

A further analyses has been carried out, in order to investigate the influence of a potential phase delay between the horizontal and the vertical components of the ground motion. For each accelerogram, several displacements have been computed by fixing the horizontal component and continuously shifting the vertical one, up to a time delay equal to its predominant period.

The most significant variations in displacements were obtained for Calitri accelerogram, combining WE horizontal component with the vertical (DU) motion. The results are shown in Fig. 7, where the displacement time-histories caused by the horizontal component, the horizontal plus the vertical component, and the horizontal plus the vertical component shifted by a delay time of 0.5 s (about half of the predominant period) are plotted.
Even in this case, where the most effective time delay is represented, the variations in the cumulated displacements are practically negligible.

COMMENTS AND CONCLUSIONS

The numerical analyses put in evidence the potential reduction of the final displacements (previous point 1) produced by vertical seismic motions. This is due to the upward vertical accelerations which induce downward inertia forces in the sliding mass and increase the critical acceleration values ($K_{c0} \cdot g$).

Analogous results have been obtained analysing the behaviour of retaining walls. In this case numerical results seem to be confirmed even by experimental tests recently performed by the Authors by the shaking table equipment of the Earthquake Engineering Research Centre at Bristol University (Simonelli, 2000).

The effects of vertical motion is percentually significant in the range of very low displacement values (previous point 2), which are actually negligible from the engineering point of view.
On the contrary, in the range of significant permanent displacements (previous point 3), the role of the accelerogram vertical component is always negligible, for each of the three

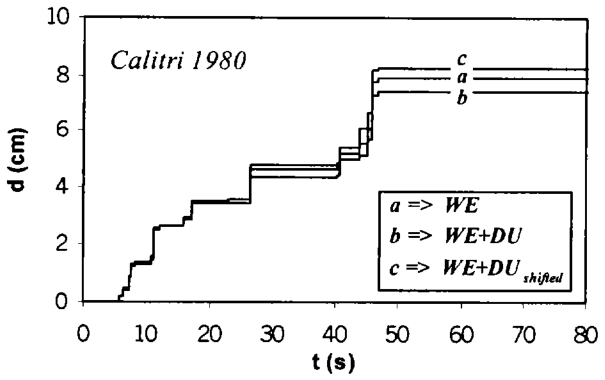


Fig. 7. Displacement time-histories for three different input motions (by Calitri 1980): WE (horizontal component), WE+DU (vertical component), $WE+DU_{shifted}$ (vertical component with a time shift ~ 0,5 s).

reference earthquakes, characterised by quite different ground motion features.

The last conclusion is confirmed even imposing phase delays between the horizontal and vertical accelerometric input motions.

The results here presented, relative to a wide data set referring to three major Italian earthquakes, are in good agreement with those obtained for free-draining soils by Ling et al. (1997). These Authors investigated the effect on displacement of vertical input motions, both harmonic functions and real worldwide accelerograms, and enhanced that the displacements yielded by real earthquakes are considerably smaller compared to those calculated assuming harmonic motions (Ling and Leshchinsky, 1995).

In conclusion, the evaluation of the critical acceleration of slopes is influenced by the presence of the vertical component of the ground motion, which can produce both positive and negative effects on the potential sliding phenomenon. The final variations in induced displacements depend on the coupling between the amplitude and frequency of the horizontal and the vertical components of the motion. The analyses of real earthquakes highlights that the effects of recorded vertical accelerogram are practically negligible, confirming the effectiveness of displacement analyses performed utilising only horizontal accelerograms as input motion.

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