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EVALUATION OF SEISMIC DISPLACEMENTS OF CANTILEVER RETAINING WALLS

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ABSTRACT

A simplified dynamic analysis method is proposed to predict the seismic sliding displacement of cantilever retaining walls by considering the deviation of thrust due to the variation of shear stresses along the ideal vertical plane passing through the heel of the wall, developed in backfill during earthquakes. This method uses Newmark sliding block concept but varies the yield acceleration according to the thrust and thus to the earthquake, to calculate the permanent displacement. A parametric study was performed in order to account for different size of the wall and backfill properties as well as different accelerometric Italian earthquakes. The proposed method is verified by comparing the predicted displacements with the results of dynamic numerical analysis performed by FLAC code.

Keywords: cantilever walls, displacements, numerical analysis, earthquake, seismic design.

INTRODUCTION

In common practice, to evaluate the safety state of a cantilever wall the trust is evaluated with respect to an ideal vertical surface that starts at the end of the base and reaches the ground surface (Huntington, 1957). This force is evaluated according to various procedures. In a wall with a long internal base, the Rankine conditions can develop freely because do not interfere with the vertical stem of the wall. The failed zones are confined inferiorly by two failure surfaces that start at the end point of the heel. The inclination of the active earth pressure along the vertical surface through the heel of the wall is assumed by Huntington (1957) to be constant and depends on the geometry of the ground surface for plane backfill.
Authors recently proposed a New Stress Pseudostatic Plasticity Solution (*NSPPS*) for the evaluation of active pressure. This method is easily adapted to the case of an earthquake assuming pseudo static conditions (Evangelista et al., 2010). It was applied to the case of a horizontal and irregular backfill allowing for the calculation of the pressure values, which were compared with those of the Mononobe-Okabe method. A comparison between the performance variables and the assumed behaviour of the soil near the wall was also carried out through the FLAC (Fast Lagrangian Analysis of Continua) numerical code (Itasca, 2000).
This paper deals with the sliding permanent displacements of cantilever walls calculated according to a modified Newmark approach by the application of the new method *NSPPS*. The results for different Italian earthquakes and geometry of the backfill were reported and were compared with that of the traditional Newmark method (1965) and those of dynamic numerical FLAC analysis.

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EVALUATION OF SEISMIC DISPLACEMENTS

Recently, many contributions have been made in Italian and international research on the application of design-performance analysis methods to geotechnical structures and in particular to retaining walls. These methods have generally been based on an extension of the model of a rigid block sliding on an inclined plane first proposed by Newmark in 1965 to evaluate the effects of earthquakes on dams and embankments.

The new technical Italian code (Norme Tecniche delle Costruzioni NTC, 2008) specifies the applicability of the method of displacement in reviews of retaining walls in the ultimate limit and serviceability limit states. In all cases, verification of the applicability of studies of movement induced by seismic action must be properly evaluated according to the relevant limit state (ULS or SLE) and life-reference work. It is obvious that the method allows for transient stability at critical conditions, at which plastic displacements occur. For retaining walls, the aforementioned movements are normally sliding along the foundation.

The assessment of permanent sliding displacement of the wall induced by an earthquake is based on determining the critical acceleration at which the resistance to motion is completely overcome. It is possible to integrate the equation of relative motion between the wall and base for the point at which it exceeded the critical acceleration and to thus determine the relative velocity of the deceleration period. In the classic approach of Newmark, the threshold acceleration value is assumed constant during the motion. Improvements to the method for gravity walls were made by Zarrabi (1979), in which the value of the acceleration threshold changes over time depending on the level of acceleration. This method was validated by testing prototypes of a gravity wall with a smooth inner facing on a shaking table (Crewe et al., 1998; Carafa et al., 1998).

In these analyses we generally adopted a rigid, perfectly plastic soil model, where the thrust is essentially independent of the history of movements of the wall. The NTC parametric analysis of this type allowed the determination of the calibration coefficients β_m to reducing seismic action in field applications, improving upon the safety of traditional pseudo static methods.

In this work the permanent sliding displacements were evaluated by the proposed pseudo-static method to determine the seismic actions that produce a sliding foundation considering that during an earthquake there is continuous variation of the shear force along the wall and, therefore, a continuous change of the inclination δ (Evangelista et al., 2010) therefore the threshold acceleration changing during the earthquake. This causes a reduction in permanent sliding compared to the results based on traditional calculations for walls with constant δ, as shown below.

APPLICATIONS TO CANTILEVER WALLS

Two walls were considered, as shown in Fig. 1. The first, Wall A, consists of a 10.80-m-high wall supporting a horizontal backfill; the second, Wall B, is 8.3 m high and retains an irregular backfill with an angle of 25° downhill of the AV surface and flat uphill. The height of the backfill uphill of the surface AV is equal for the two walls. In both cases, the backfill consists of incoherent pyroclastic soil with a friction angle φ of 30° and a unit weight γ equal to 15 kN/m^3. The subsoil consists of a thin layer of the same material above a rocky rigid formation. The length of the internal base of the walls allows the development of Rankine failure surfaces in the backfill (not intersecting the vertical stem of the wall).

It is assumed that the walls were design in a zone of a high seismicity according to Italian classification with a maximum acceleration a_{max} of 0.35g. The pseudo-static coefficient k_h = 0.1 was obtained according to the NTC (2008) by the formula:

$$k_h = \beta_M \cdot \frac{a_{\max}}{g} \tag{1}$$

where $a_{\max}$ is the maximum acceleration, assumed equal to 0.35 g, β_M is a reduction coefficient for the retaining wall, equal to 0.31 for soil from A to D, and a_g ranged from 0.2 g and 0.4 g.

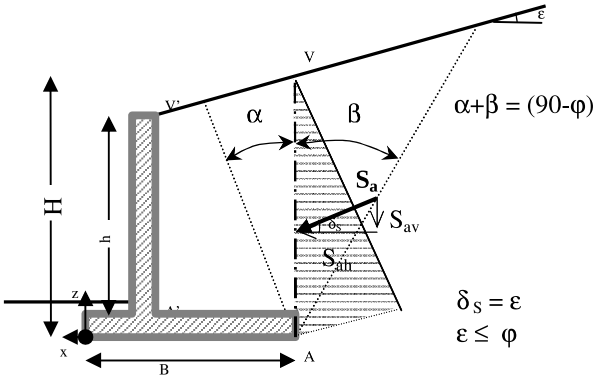
The new method *NSPPS*, in the simple case of plane backfill of slope ε, starts from a possible statically admissible stress field which satisfied all stress boundary conditions reported below:

$$\sigma_\varepsilon = \gamma \cdot \cos\varepsilon \cdot z^* - k_h \cdot \gamma \cdot \sin\varepsilon \cdot z^* \tag{2}$$

$$\tau_\varepsilon = \gamma \cdot \sin\varepsilon \cdot z^* + k_h \cdot \gamma \cdot \cos\varepsilon \cdot z^* \tag{3}$$

Where σ_ε and τ_ε are the normal and shear stress acting on plane parallel to the slope at depth z, and $z^* = z \cdot \cos\varepsilon$. Imposing the active failure conditions the new method *NSPPS* allows to determine the active pressure coefficients k_{ah} and k_{av} as a function of φ, k_h and ε (Evangelista et al., 2010a).

a)



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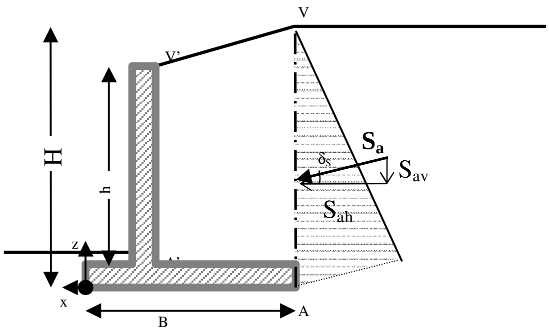


Figure 1. Active pressure against a cantilever wall supporting a soil with a regular backfill (a and irregular ground surface (b.

Applying the method *NSPPS* to Wall A under a horizontal pseudostatic coefficient k_h of 0.1 and k_v equal to 0 yielded the following components of the earth-pressure coefficients: 0.3535 for the horizontal k_{ah} and 0.1 for the vertical k_{av}, with a thrust inclination δ_{NSPPS} of 16°. The horizontal thrust component on AV is equal to 309 kN/m, which is equal to 265 kN/m on A"V. The bending moment on the stem is 883 kNm/m. The moments were calculated neglecting the inertial actions due to the weight of the wall and the tangential force acting on the inner face of the stem.

Applying the *NSPPS* method to Wall B, with the irregular backfill surface, we obtained a pseudostatic earth-pressure coefficient (k_{NSPPS}) of 0.3659 and an inclination of 20°. The horizontal thrust component along AV is 300 kN/m. Under the shelf vertical, A"V, the horizontal thrust component is 145 kN/m. The maximum bending moment is 362 kNm/m. The application of the method on this case, that follows the route of Huntingthon (1965), was reported in the previous paper (Evangelista et al., 2010b).

The displacements induced on the wall from the different seismic inputs were calculated using the classical Newmark model (1965) and the new method proposed by the Authors. It is important to stress that in this method the critical acceleration varies with time as function of the inclination (δ) of line of action of earth pressure, unlike the classical Newmark method.

For Wall A, if δ equal to 0º is assumed we made evaluate the critical acceleration equal to 0.233 *g*; if δ is assumed equal to 16°, according to the *NSPPS* assumptions made above, the critical acceleration grows and is equal to 0.281 *g*.

For Wall B the following values of threshold acceleration were calculated: 0.234 *g* and 0.290 *g* for δ equal to 9.5º and 20.6°.

Four accelerometric time histories were selected from a database of records of Italian seismic events (Scassera et al., 2006). The signals were scaled to values of a_{max} equal to 0.35*g*, where a_{max} is the maximum acceleration expected in a zone of a high seismicity according to Italian classification, Fig. 2. The main features of the recorded accelerograms are listed in Table 1; the frequency content of the waveform is quantified through the predominant period, T_p, corresponding to the maximum spectral acceleration in an acceleration-response spectrum (computed for 5% viscous damping) and through the mean period, T_m, as defined by Rathje et al. (1998) on the basis of the Fourier spectrum of the signal. Actually, T_m should provide a better indication of the frequency content of the recordings because it averages the spectrum over the whole periodic range of amplification.

The cumulative permanent displacements calculated, for example, for the accelerogram of San Rocco were reported in Fig. 3. The displacements obviously decrease with increasing thrust inclination. The comparison between the cumulative displacements evaluated with the proposed method and that evaluated with the traditional method of Newmark was reported in Fig. 3.

It is noted that the displacements obtained with δ greater then 0 are smaller than those obtained with the traditional method. Obviously the same results are obtained for the two walls and the various inputs used in the Figures 4, 5 and 6 reported for completeness.

But if we compare, for the same method of calculation, the displacements obtained for different accelerograms observed different maximum displacements and therefore the maximum acceleration is not the only factor that influence the permanent displacement of the wall.

Instead, comparing the results between the two walls analyzed, with the same hight of thrust (AV Fig. 1), it is noted that the wall A undergoes less displacements of wall B consistent with the fact that the former is lighter.

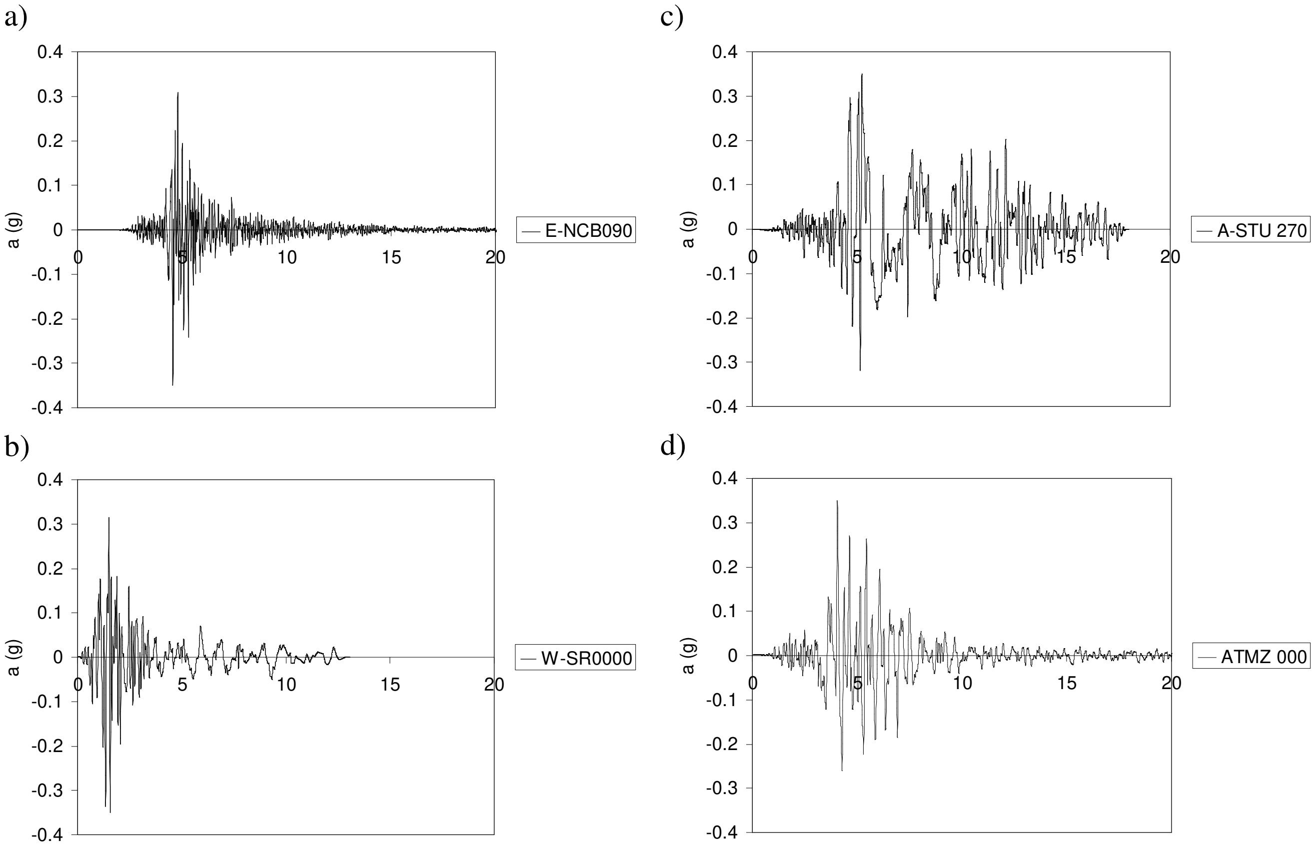


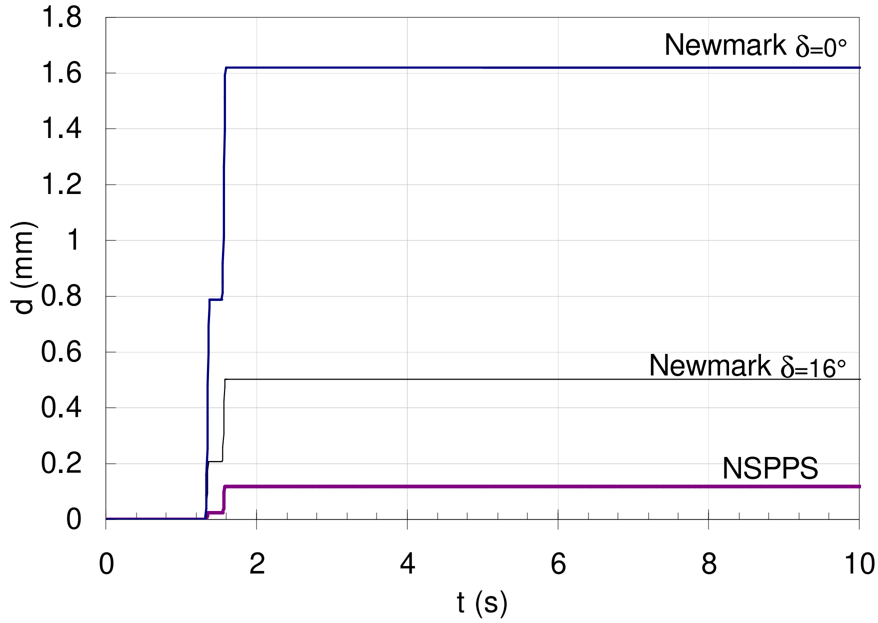
Figure 2. Accelerograms scaled at 0.35 g: a) Norcia; b) San Rocco; c) Sturno; d) Tolmezzo.

Table 1. Strong motion features.

Site (Earthquake)	*PGA* (g)	T_m (s)	T_P (s)	I_a (cm/s)
Norcia (Umbria-Marche 1997)	0.38	0.17	0.12	34.25
San Rocco (Friuli 1976)	0.09	0.29	0.10	3.22
Sturno (Irpinia 1980)	0.32	0.86	0.20	139.35
Tolmezzo (Friuli 1976)	0.35	0.39	0.26	78.65

PGA Peak Ground Acceleration; T_m Mean Period; T_P Predominant Period; I_a Arias Intensity.

a)



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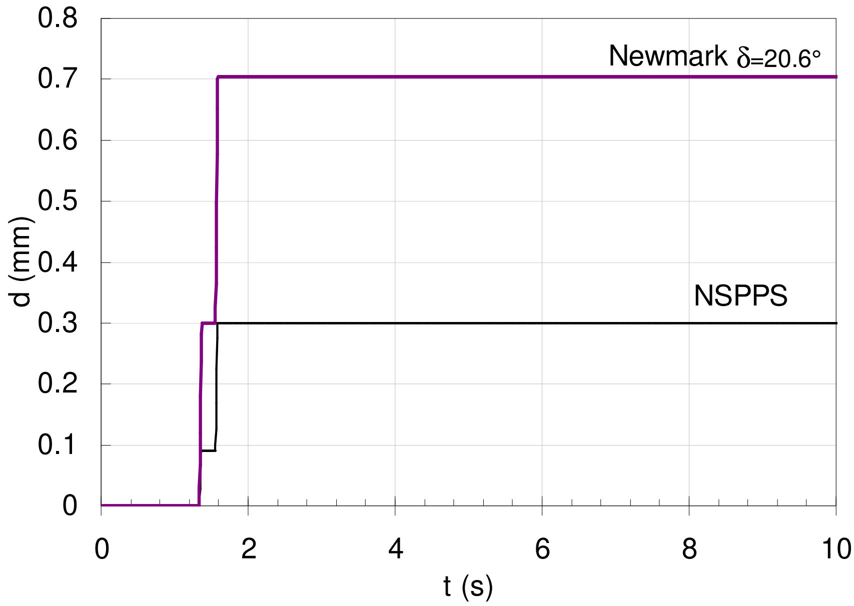
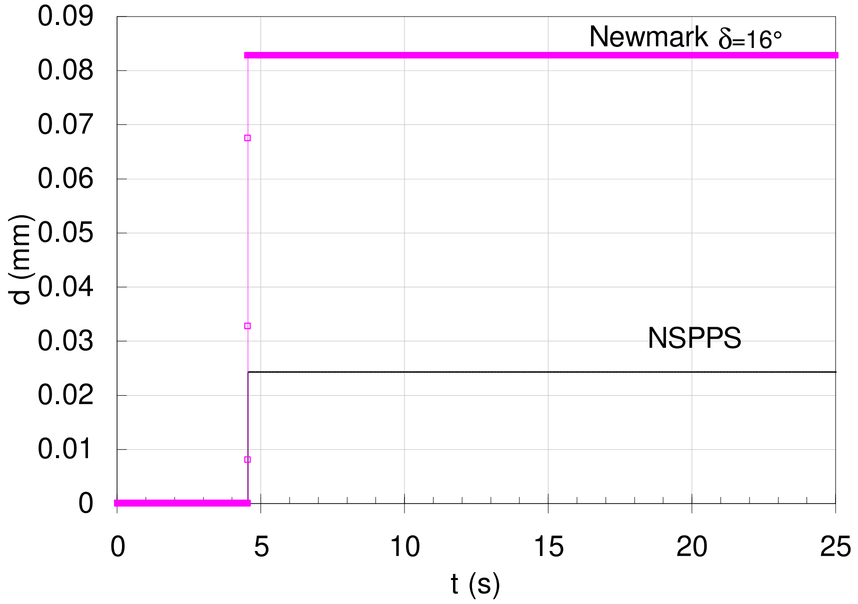


Figure 3. Comparison between permanent displacements of wall A (a) and B (b) due to the San Rocco accelerogram evaluated by *NSPPS* and Newmark (1965) approaches.

a)



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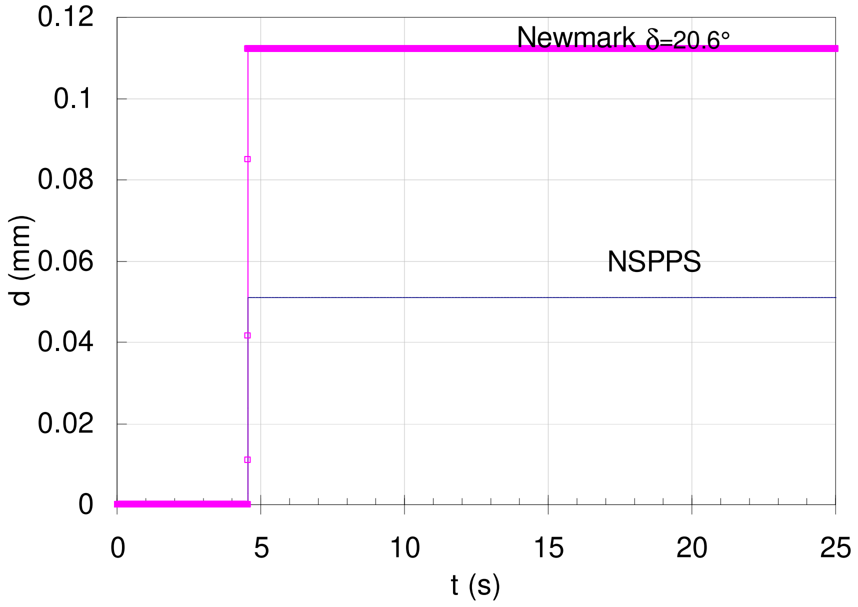
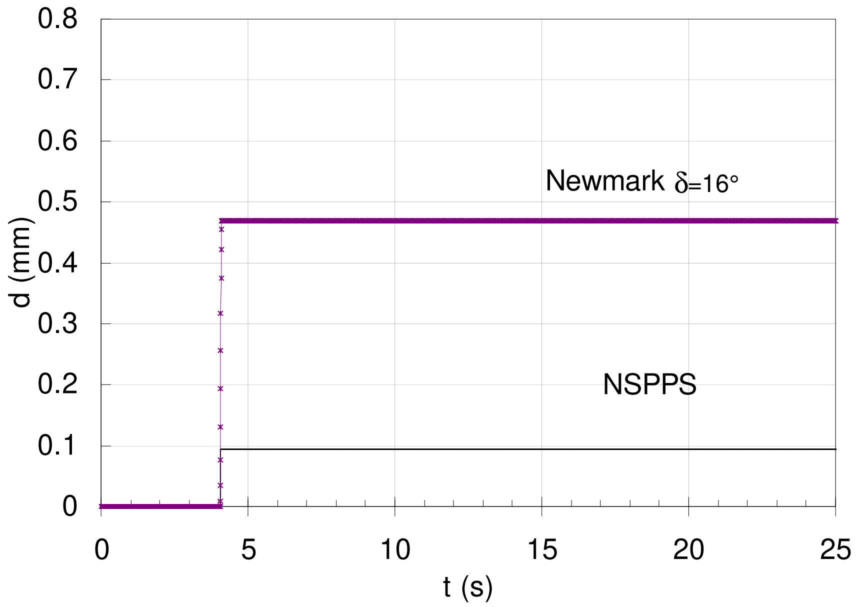


Figure 4. Comparison between permanent displacements of wall A (a) and B (b) due to the Norcia accelerogram evaluated by *NSPPS* and Newmark (1965) approaches.

a)



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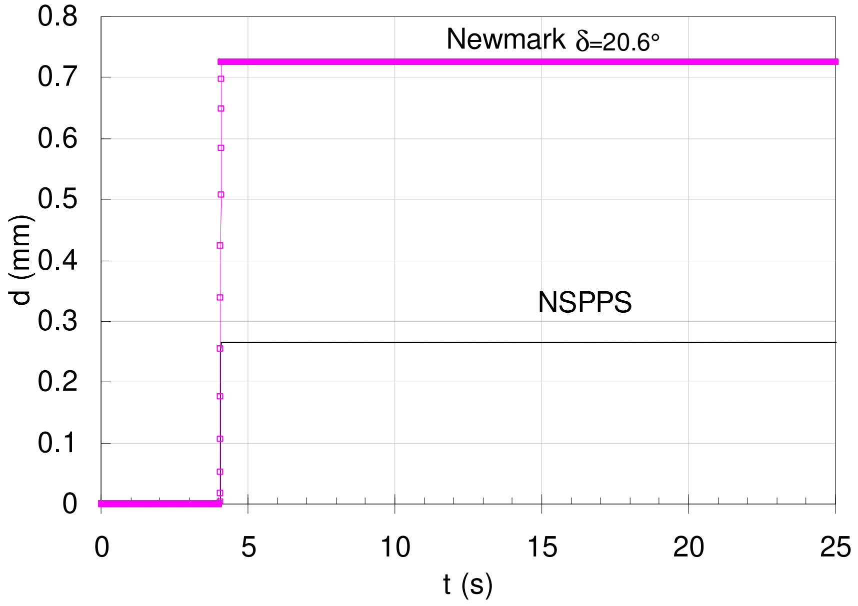
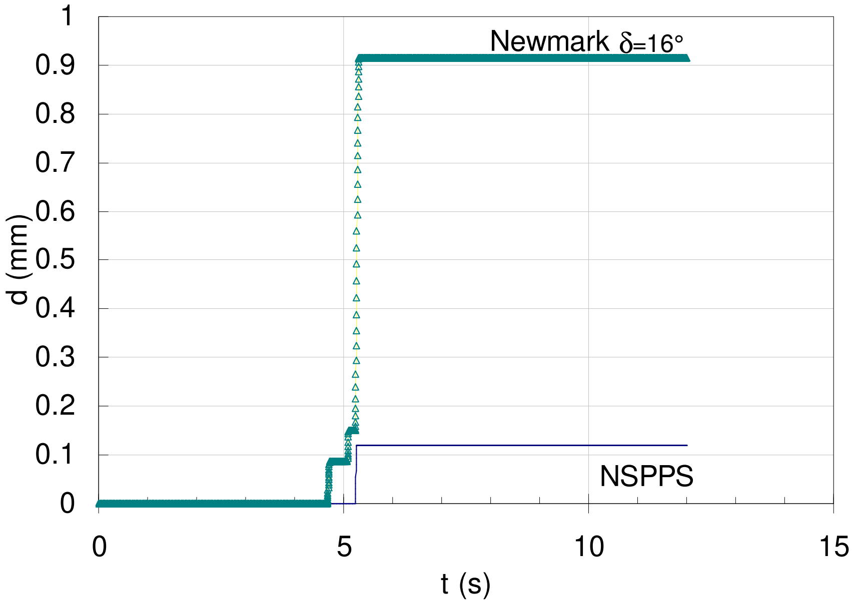


Figure 5. Comparison between permanent displacements of wall A (a) and B (b) due to the Tolmezzo accelerogram evaluated by *NSPPS* and Newmark (1965) approaches.

a)



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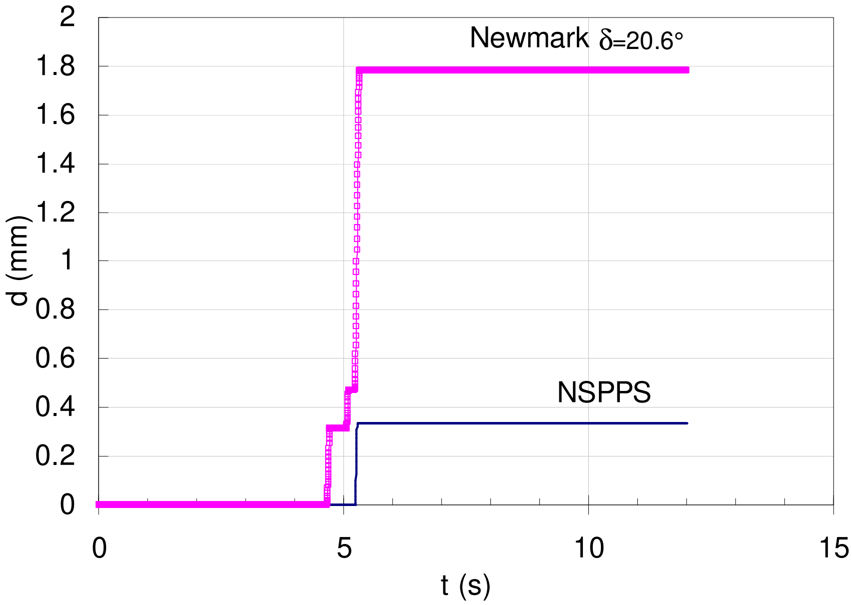

Figure 6. Comparison between permanent displacements of wall A (a) and B (b) due to the Sturno accelerogram evaluated by *NSPPS* and the Newmark (1965) approach.

FLAC MODELS

The two wall-soil systems were analysed using the FLAC code, which utilises an explicit finite-difference method for solving differential equations. For both models we used a square grid 0.2 m on each side. The backfill was modelled as an elastoplastic constitutive model (elastic modulus E = 50 MPa, and Poisson coefficient $\nu = 0.3$) in conjunction with the Mohr-Coulomb yield criterion (cohesion c = 0; φ friction angle = 30°, and dilatancy $\psi = 0$). The wall was modelled as elastic with $\gamma_c = 24$ kN/m^3, $E_c = 20$ GPa, and $\nu_c = 0.1$. The subsoil consists of a thin layer of the same material above a rocky rigid formation. It is preferable not to use interface elements between the different materials but rather small layers of chosen properties. The model was created by the activation of the elements constituting the wall and subsequently those of the backfill for successive layers of a thickness of one metre (Green & Ebeling, 2003). The results in the static field are reported in a previous work (Evangelista et al., 2009; 2010).
In the pseudostatic analysis, a constant acceleration 0.1 g was applied at all points of the model, as said before. This analysis was carried out in dynamic-field mode using the viscous boundary conditions of Kuhlemeyer & Lysmer (1973), with a Rayleigh damping of 5%.
Four accelerometric time histories of an Italian earthquake were utilised in the dynamic analysis (table 1). The dynamic analysis was performed both in the absence and in the presence of a Rayleigh damping of 5%.
Figure 7 shows, for instance, the displacements calculated from FLAC analysis for the Sturno accelerogram for Wall A. We observe a peak of displacements that is likely to be larger than the residual ones. Figure 8 shows, for instance, the displacements calculated from FLAC analysis for the Tolmezzo accelerogram for Wall B.
If we compare the residual permanent displacement evaluated with simplified dynamic analyses we observe that the FLAC displacements are clearly less than those evaluated with the classic Newmark approach and are slightly lower than those assessed with the procedure proposed by the Authors.
The lack of case histories regarding the damage or displacement of cantilever wall during or after an earthquake (in cohesionless backfills) could be suggest that the proposed method are more realistic than the current pseudo-static analysis. Nevertheless the lack of well documented case histories limits the conclusion of the proposed approach. For this reason is currently carried out an experimental activity on prototypes on shaking table.

CONCLUSIONS

We report the results of analyses performed for the evaluation of permanent sliding displacements in seismic conditions of two cantilever walls characterised by a constant height of the ideal surface AV passing through the heel of the wall (Fig. 1), against which the traditional approaches were used to assess the destabilising thrust exerted by the backfill. The latter was horizontal for case A and inclined at 25° in case B downhill to AV surface and flat uphill. The size of the internal base allows the development of Rankine failure surfaces.
The displacements of the two walls was analysed through different approaches: a Newmark analysis and a dynamic analysis using the FLAC code. In the former analysis the thrust and its inclination δ were evaluated by a new method, *NSPPS,* proposed by the authors in previous works for regular and irregular backfill (Evangelista et al., 2010a and b).
The comparison between the *NSPPS* method and traditional pseudo-static design approaches and numerical results suggests that the former are more realistic than the current pseudo-static analysis. Nevertheless the lack of well documented case histories limits the conclusion of the proposed approach. For this reason is currently carried out an experimental activity on prototypes on shaking table.

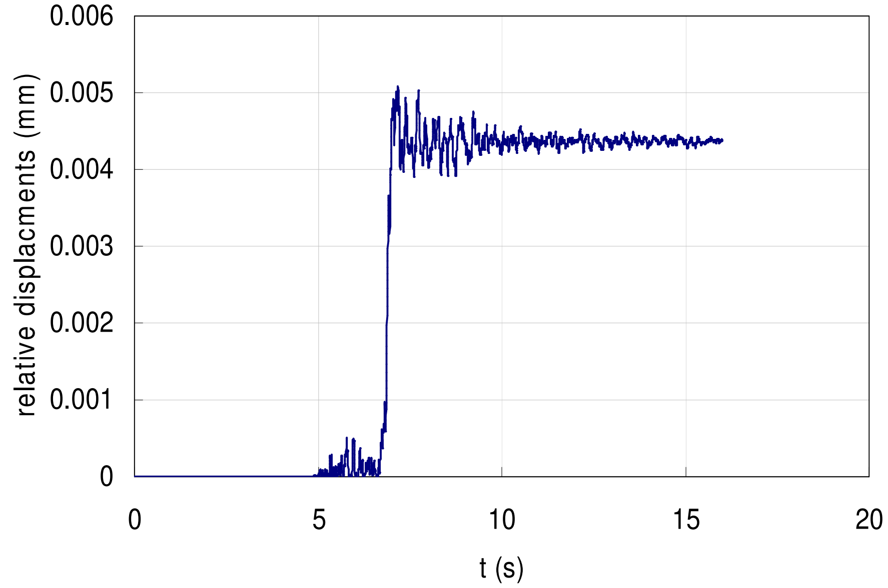

Figure 7. Permanent displacements of wall A due to the Sturno accelerogram evaluated by Dynamic FLAC analysis.

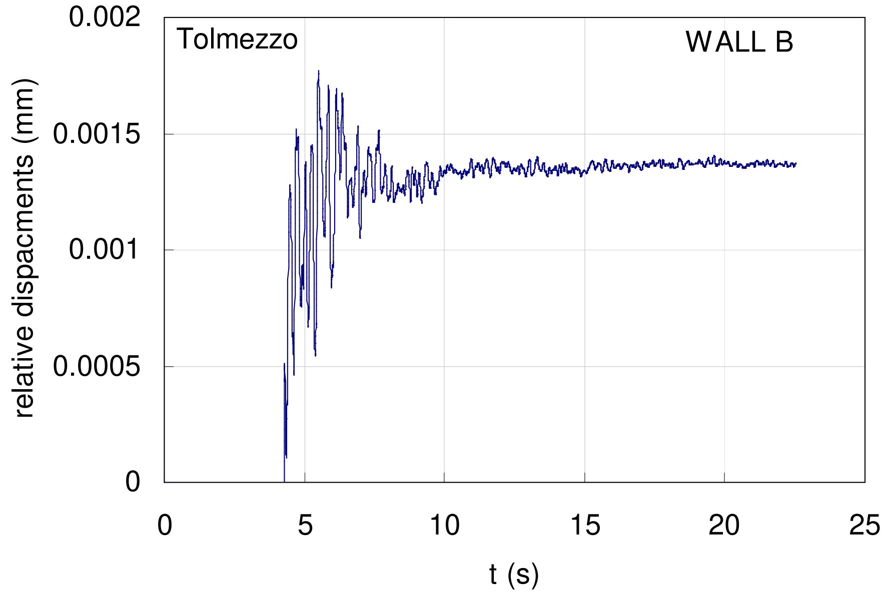

Figure 8. Permanent displacements of wall B due to the Tolmezzo accelerogram evaluated by Dynamic FLAC analysis.

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