# The behaviour of Acciano earth dam during the Umbria-Marche earthquake of September 1997

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*Summary*

The earthquake of 26 September 1997, one of the largest seismic events of the last 20 years in Italy, caused significant damage in a large area of Umbria and Marche regions. The national strong motion network recorded very high peak ground accelerations (PGA), whose maximum value was of about 0.56 g at the town of Nocera Umbra, and significant local soil amplifications. The Acciano zoned earth dam, sited close to Nocera Umbra, suffered damage to the crest structure, consisting mainly in longitudinal cracks, maximum settlement of about 20 centimeters and lateral displacement of 10 centimeters in the downstream-upstream direction. The behaviour of the dam during the main shocks is examined in the paper by using the Newmark's method of analysis and a comparison is made between computed and observed dam deformations. Moreover an attempt is made to correlate the conventional factors of safety deriving from pseudo-static approach with allowable deformations. The lessons learned from the "real scale experiment made by Nature" consist in the confirmation of the usefulness of the Newmark's method in the assessment of the behaviour of earth dam during strong earthquakes and that the minimum factors of safety prescribed by italian code granted the dams to withstand PGA up to 3-4 times the constant level of acceleration introduced in the pseudo-static approach.

## 1. Introduction

On September 26th 1997, at 2:33 AM local time, an earthquake of magnitude Mw=5.5 occurred near Colfiorito, at the border of Umbria and Marche regions in central Italy, causing many damage mostly to ancient masonry buildings. Nine hours later, a stronger event (Mw=6, Ms=5.9) carried out the destruction of the area, 11 people were killed, 126 injured and 25,000 homeless [SSN-ENEL, 1998].

In the framework of emergency activity, inspections to all the dams located in the area were executed. Near the epicenter, 11 km far from the medioeval town of Nocera Umbra, an earth dam built to bar the Acciano stream, beared evidence of large deformations and cracking of the crest, even if no global instability phenomena apperared. The other dams, located at greater distance from the epicenter, did not show significant damage to the structures or to the outlets.

The observed behaviour of Acciano dam, together with the availability of data concerning both materials and earthquake ground motion, suggests to examine closely the seismic response of the structure with the aim to compare the *"real scale experiment made by Nature"* to the theoretical analyses normally used in the engineering evaluations.

The case history is of outmost importance also for the outstanding effort of re-evaluate the safety of existing dams in Italy [SND, 1995].

## 2. Earthquake ground motion

In the effort of explaining the response of a structure to an earthquake, is of fundamental importance the availability of ground motion recording. In the Umbria-Marche eathquake of September 1997 a large number of stations of the national accelerometric network (RAN) was operating. The records give a good description of the earthquake motion, both in time and space, and the available data have been analysed by many expert teams [Rovelli *et al.*, 1998, Sabetta et al, 1999, GNDT-SSN, 1999, Marsan *et al.* 2000]. In Fig. 1 epicenter, causative faults and location of the accelerometric stations are shown for the 11:40 main shock; in the figure the macroseismic MCS intensity and the recorded peak ground accelerations (PGA) are also reported. Local site effects have been pointed out, as the interesting case of Nocera Umbra station, where the records show amplification factors higher than 2 for PGA and over 5 for Arias Intensity caused by geological site conditions. In Figs. 2 and 3 accelerograms and spectral values of Nocera Umbra and Colfiorito are compared. In Fig. 3 a theoretical attenuation law curve (obtained from statistical elaboration of Italian earthquakes data) and the Italian seismic code spectrum curve are also plotted. The latter one is multiplied by a factor of 8, given by the product of the factor corresponding to the ultimate limit state ($\psi=2$, usually assigned to r.c. materials) and of a conventional behaviour factor usually adopted (q=4, an approximation of the ratio of the seismic forces that the struc-

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* Dams National Authority (Italy).

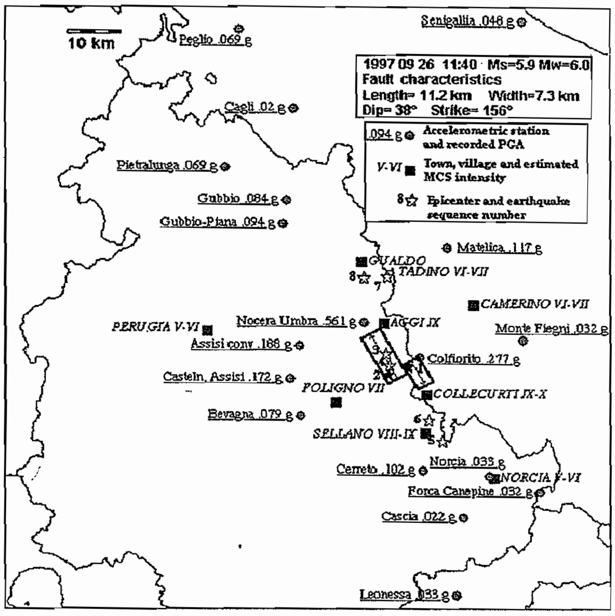

Fig. 1 – Epicenters, causative faults and location of the accelerometric stations trigged by the main shock of september 26, 1997, 11:40 [after SABETTA *et al.*, 1999].

*Fig. 1 – Epicentri, faglie e localizzazione delle stazioni accelerometriche attivate durante il terremoto del 26/9/97 ore 11:40 [da SABETTA* et al.*, 1999].*

ture would experience if its response was completely elastic, with 5% viscous damping, to the minimum seismic forces that can be used in design, Eurocode 8,2000). It can be observed that the attenuation law and the code curve fit well the Colfiorito spectral accelerations, while the Nocera Umbra spectrum shows extremely high values that can never be anticipated by statistical analysis if local soil and geological conditions are disregarded.

## 3. Acciano earth dam

The barrage of the Acciano earth dam was built in the years 1974-1980 to control the seasonal flow of water with an artificial resorvoir of 1.7 million of $m^3$. The zoned earth dam, whose cross-section is shown in Fig. 4, reaches a maximum height of 28.4 meters. The shells are unusually symmetric and were built by dry compaction of two different materials: the zone above level 513.00 m a.s.l. with rockfill and the part below with a gravelly sand. A clayey silt was used for the core. The embankment is founded over an alluvial soil, of a maximum depth of 20 meters in the central valley, whose upper layers are fine graded. To re-

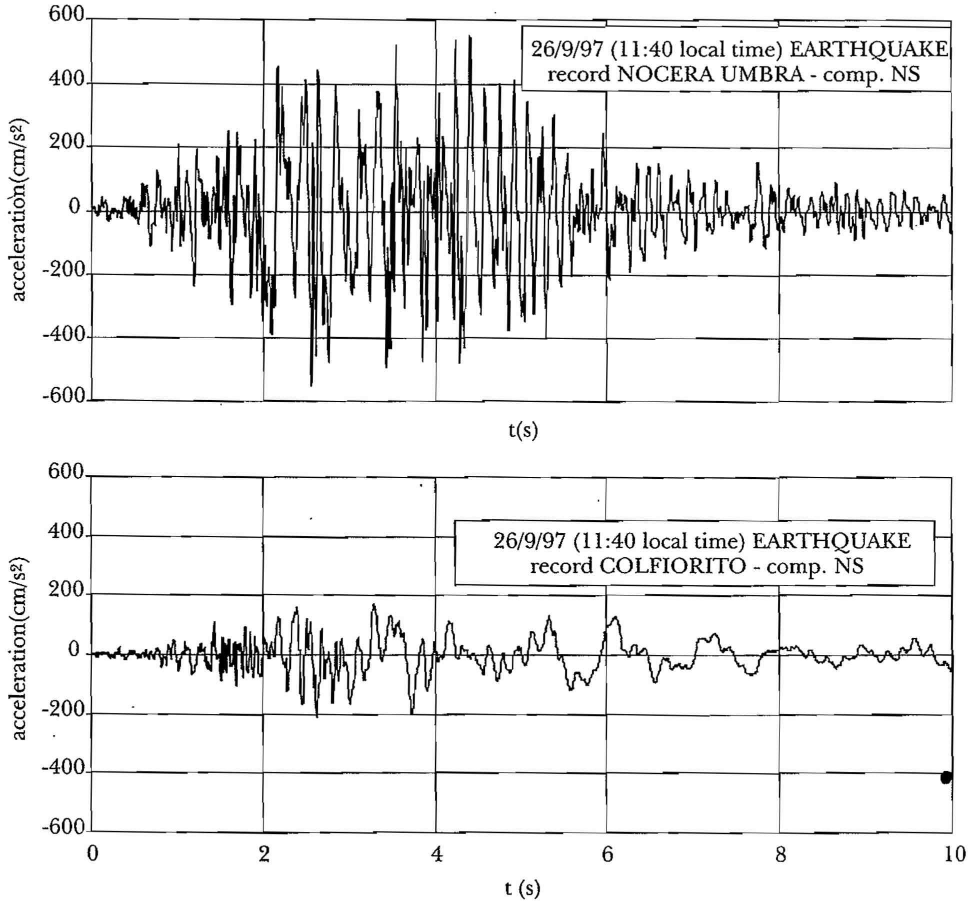

Fig. 2 – Accelerograms recorded at Nocera Umbra and Colfiorito (NS comp.) during the main shock of september 26, 1997, 11:40 local time.

*Fig. 2 – Accelerogrammi registrati a Nocera Umbra e Colfiorito (comp. NS) durante l'evento del 26 settembre 1997, 11:40 ora locale.*

duce the seepage, a concrete diaphragm wall was built under the core till the bedrock.

The geotechnical characteristics of the soils, assessed both in design and construction stages, are reported in Tab. I.

Monitoring of the dam behaviour consists of datum points for assessing vertical and upstream-downstream surface movements (6 on the crest and 6 on the downstram bank) and of 8 Casagrande piezometers located downstream. Reservoir level, precipitation and air and water temperature are also recorded.

In the design stage the limiting equilibrium analyses considered only global stability of the embankment and leaded to safety factors higher than those fixed by the regulation in force, equal to 1.4 and 1.2 for static and seismic conditions respectively [D.M. LL.PP., 1982]. No attention was addressed to the stability conditions of the upper part of the shells, where the infinite slope model gives a safety factor equal to 1.17 in static condition and decreasing up to 1 for the pseudo-static acceleration of 0.07 g prescribed by the italian regulation.

Tab. I – Geotechnical parameters of the zoned earth dam and of the foundation soil.
*Tab. I – Parametri geotecnici dei materiali utilizzati nella diga e nei terreni di fondazione.*

| Material | saturated unit weight $\gamma$(kN/m$^3$) | cohesion c' (kPa) | shear strength angle $\phi$' (°) |
|---|---|---|---|
| Core | 21 | 30 | 25 |
| shell (rockfill) | 23 | 0 | 40 |
| shell (gravelly sand) | 24 | 0 | 35 |
| Alluvium | 21 | 0 | 30 |

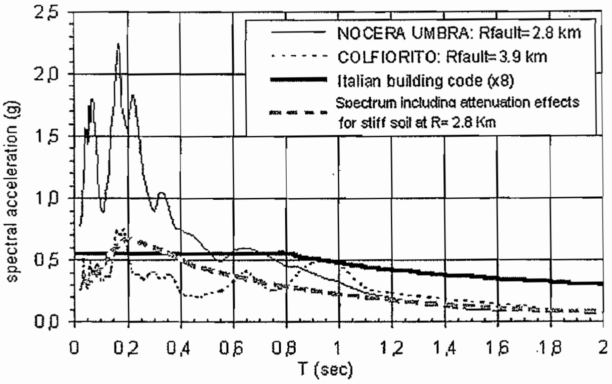

Fig. 3 – Absolute acceleration response spectra (5 % damping, N-S component) of Nocera Umbra and Colfiorito during the main shock of september 26, 1997, 11:40 [after SABETTA *et al.*, 1999].
*Fig. 3 – Spettri degli accelerogrammi (smorzamento 5 %, componente N-S) registrati a Nocera Umbra e Colfiorito durante il terremoto del 26/9/97 ore 11:40 [da* SABETTA et al.*, 1999].*

### *3.1. Deformations and cracking of the dam*

After the first shock at 02:33 AM local time, visual inspection of the dam did not reveal any evidence of damage. But after the second event, at 11:40 AM local time, a wide crack pattern appeared in the asphalt paving of the crest (Fig. 5). Longitudinal cracks, close to the crest edges, and transversal ones, near the extreme ends of the dam, were observed. Settlements up to 20 cm of the rigid r.c. edges of the crest road were measured in the main cross-section, where also a lateral spreading of about 10 cm was also found out. The downstream bank at level 513.00 m a.s.l. settled about 1-2 cm.

Water level at the time of the earthquake was relatively low, about 504 m a.s.l., and the reservoir was emptied in a few days.

In the subsequent months, settlements of the dam increased of only a small percentage: the time

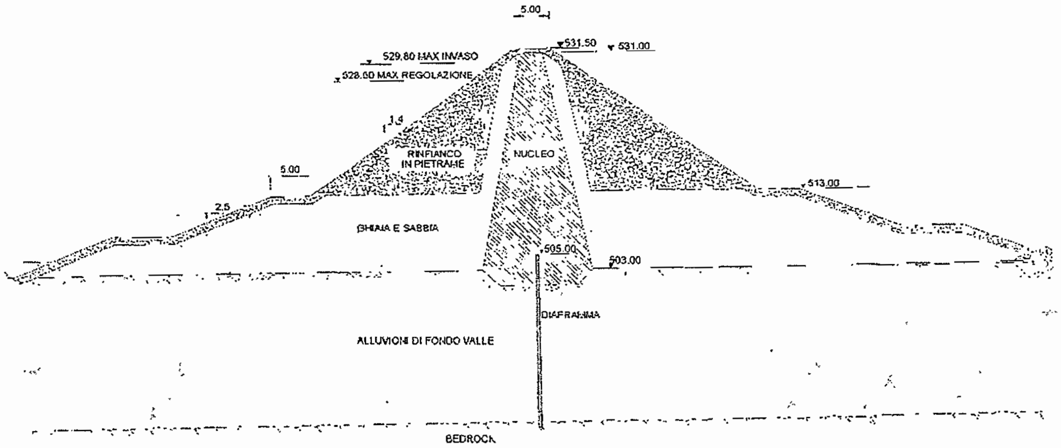

Fig. 4 – Acciano earth dam cross section.
*Fig. 4 – Sezione trasversale della diga di Acciano.*

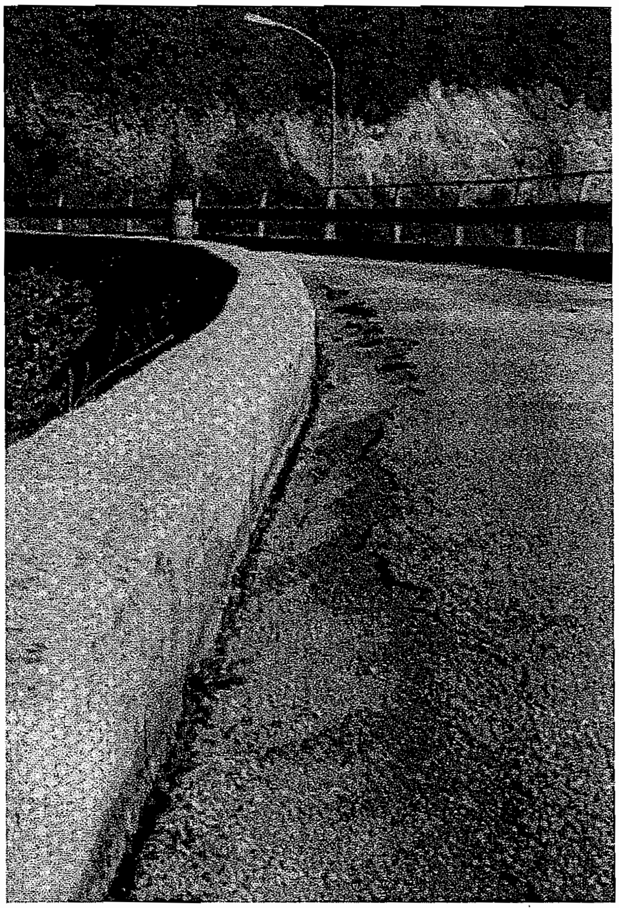

Fig. 5 – Acciano earth dam: view of the crest after the main shock of sept. 1997 11:40 local time.
*Fig. 5 – Vista dello stato del coronamento dopo il sisma del 26 settembre 1997, ore 11:40 ora locale.*

effect may be due to the subsequent minor seismic events and to the dissipation of pore pressure increases in the foundation soil: in fact soon after the September 26 earthquake an increase of p.p., up to 0.05 MPa, was measured in the alluvium.

### *3.2. Evaluation of the seismic response of the dam*

Both the knowledge of dam characteristics and the availability of ground motion records let possible to compare the earthquake induced displacements with theoretical previsions normally used in engineering evaluations. Although fundamental data are available, major uncertainities can affect the results of analyses; to minimize the errors, it seems better to use semi-empirical predictive relations, based on the original NEWMARK's method [1965], than referring to more sophisticated models, such as non linear F.E.M., that require a closer description of the mechanical behaviour of the soils and more detailed information regarding both free-field motion and soil-structure interaction effects.

The Newmark's method allows the computation of the permanent displacement of a slope, subjected to an earthquake, assuming that the motion occurs along arcs or planes as in the usual static analysis of stability. Direct integration can be used to compute the magnitude of the dynamic motions produced by earthquakes or other shocks. A fundamental parameter of the analysis is the critical acceleration $K_c$, i.e. the pseudo-static acceleration corresponding to a unit safety factor Fs in the limit equilibrium analysis.

Whereas in static condition a value of Fs=1 cannot exist, if not at the cost of large displacements, during an earthquake the condition Fs=1 may instantly be tolerated, leading usually to small co-seismic deformations. The maximum displacement is controlled by magnitude and duration of earthquake inertia forces, geometry of the slope and undrained strength of the soils, factors summarized in the ratio $K_c/K_{max}$ between the critical acceleration $K_c$ and the peak acceleration $K_{max}$. Computed settlements are then compared with allowable ones in term of ultimate and serviceability limits.

Several methods, based on the original Newmark procedure, have been proposed for the evaluation of co-seismic deformations: besides the ratio $K_c/K_{max}$, SARMA [1975] introduced in the analysis the effect of the predominant period To of the acceleration record; MAKDISI and SEED [1978] accounted for the influence of the magnitude M of the earthquake; AMBRASEYS *et al.* [1995] gave relations depending on surface wave magnitude Ms, source-site distance and focal depth; CRESPELLANI *et al.* [1998] used , instead of the magnitude M, the destructiveness potential factor $P_D$ , a synthetic representative indicator of the whole earthquake record depending on the Arias intensity $I_A$ [ARAYA and SARAGONI, 1984].

The stability condition of the Acciano earth dam has been analyzed using the modified Bishop method of slices. In Fig. 6 the results obtained for the downstream slope are shown: in static state, the safety factors are 1.69, 1.54 and 1.18 for the lower, medium and upper circles respectively. In Fig. 7 the safety factors versus the horizontal pseudo-static acceleration $K_h$ are plotted for the three groups of circles of the upstream and downstream slopes. Critical acceleration values $K_c$ are shown in Tab. II.

With reference to the Newmark's method of analysis, the maximum permanent displacement induced by an earthquake can be computed using two different procedures:

a) referring only to the ratio $K_c/K_{max}$ , charts or equations given by the b.m. Authors;

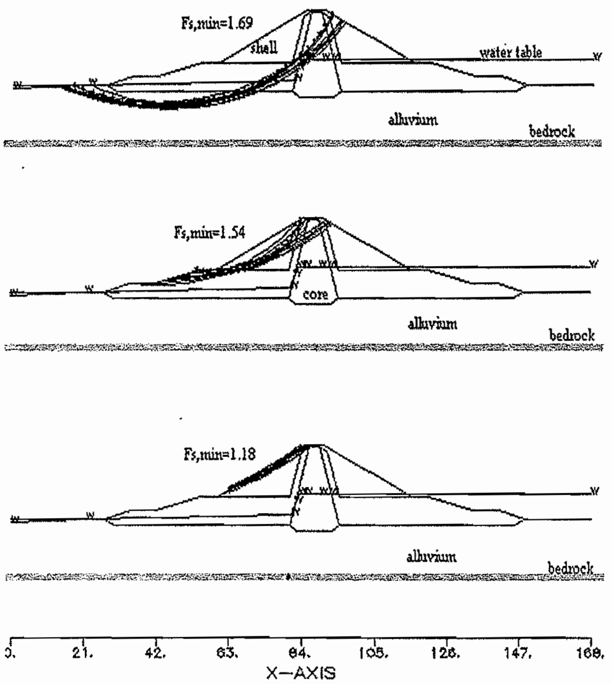

Fig. 6 – Acciano earth dam: static safety factors for different zones of the downstream shell.

*Fig. 6 – Diga di Acciano: fattori di sicurezza in condizioni statiche per diverse famiglie di superfici di scorrimento interessanti il paramento di valle.*

b) if also the time-histories of accelerations are available, a direct integration of the equation of motion is performed to compute the maximum displacement.

Both procedures have been followed for the Acciano dam with the aim of comparing the results of the semi-empirical relations, suggested by the Authors, and those obtained by direct integration with the measured settlements.

In Tab. IV the maximum values of the permanent displacements s, computed using the statistical data proposed by the a.m. Authors, are shown for two different PGA: one referred to Nocera Umbra station ($K_{max}$=0.56) and the other to Colfiorito station ($K_{max}$=0.28). In the table the main parameters introduced in the semi-empirical relations are pointed out: To (fundamental period of motion), M (magnitude), r (ipocentral distance), $P_d$ (destructiveness potential factor of the quake, i.e. the Arias intensity $I_A$ of the accelerogram divided by square number of the zero crossing per second).

Tab. II – Critical acceleration values for upstream and downstream circles.

*Tab. II – Valori dell'accelerazione critica per i paramenti di monte e di valle.*

| | ZONE | $K_c$ (g) |
|---|---|---|
| downstream | Lower circles | 0.25 |
| | Medium circles | 0.175 |
| | Upper circles | 0.08 |
| upstream | Lower circles | 0.22 |
| | Medium circles | 0.15 |
| | Upper circles | 0.08 |

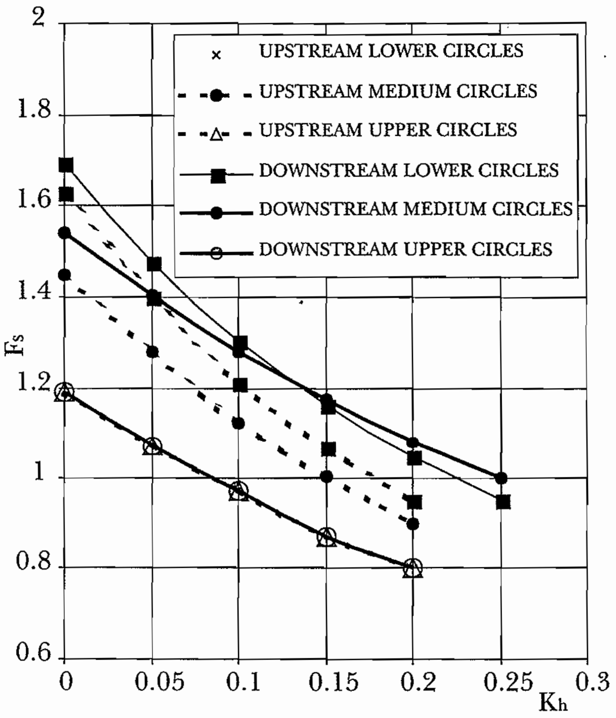

Fig. 7 – Acciano earth dam: safety factors vs pseudo-static horizontal accelerations.

*Fig. 7 – Diga di Acciano: andamento del coefficiente di sicurezza Fs in funzione dell'accelerazione pseudostatica orizzontale.*

Permanent displacements computed using Nocera Umbra record are not consistent with the observed dam behaviour, for every one of the semi-empirical relations, because accelerograms are affected by site effects that give amplification factors in the range of 3-5 of the spectral values. Colfiorito record gives a better approximation of the measured displacements for all the relations, with the exception of Newmark's one that does not fit well the data because of the higher level of acceleration considered in the original analysis.

Of great interest is the Ambraseys relationship, that gives the highest degree of accuracy in assessing permanent displacements for medium, lower and upper failure surface. The uncertainity bands are plotted in Fig. 8 for M=6 and r=11 km for the 02:33 and 11:40 local time Colfiorito records. Reliability of Ambraseys relationship is also confirmed by the comparison of the settlements computed by means of direct integration of the earthquake records (symbols in Fig. 8).

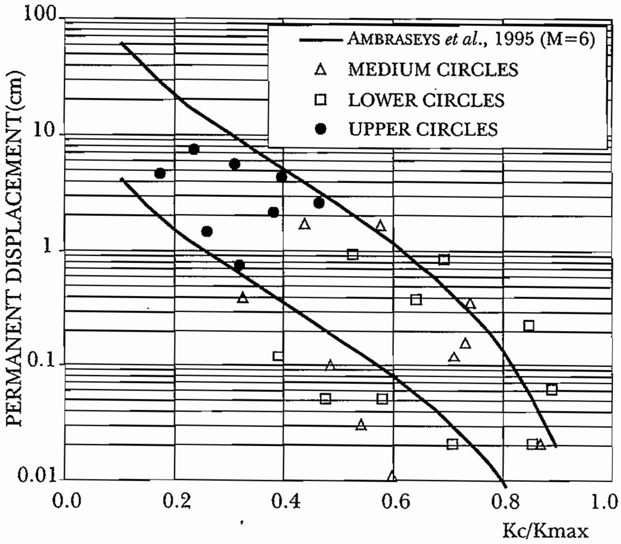

Fig. 8 – Acciano earth dam: permanent displacements computed for two main shocks of September 26, 1997, 11:40 local time.

*Fig. 8 – Diga di Acciano: Spostamenti permanenti calcolati per i due eventi sismici principali del 26 settembre 1997 (02:33 e 11:40 ora locale).*

## 4. Safety Factors

How close is the connection between safety factors and allowable settlements is a matter of great interest. In the previous discussions it was put in evidence that both $F_s$ (Fig. 7) and permanent displacements s (Fig. 8) decrease rapidly as functions of $K_h$ and the ratio $K_c/K_{max}$ respectively.

On the one hand assuming for the sake of semplicity a linear trend of $F_s$, instead of the theoretical hyperbolic law, it is possible to state:

$$F_s = F_{so} + (F_{s1} - F_{so}) \frac{(K_h - K_{ho})}{(K_{h1} - K_{ho})} \qquad (1)$$

where $F_{so}$ , $K_{ho}$ , $F_{s1}$ ,$K_{h1}$ are safety factors and horizontal pseudo-static coefficients in static and seismic conditions respectively. Being $K_{ho} = 0$, the above expression becomes:

$$F_s = F_{so} + (F_{s1} - F_{so}) \frac{K_h}{K_{h1}} \qquad (2)$$

For $K_{h1} = K_c$ the coefficient $F_{s1} = 1$ and so we have:

$$F_s = F_{so} - (F_{so} - 1) \frac{K_h}{K_c} \qquad (3)$$

and then

$$\frac{K_c}{K_h} = \frac{(F_{so} - 1)}{(F_{so} - F_s)} \qquad (4)$$

On the other hand, referring to Fig. 8, a treshold value $\eta$ for the ratio $K_c/K_{max}$ may be introduced to state a field of allowable permanent displacements :

$$\frac{K_c}{K_h} > \frac{K_c}{K_{max}} = \eta \qquad (5)$$

and at the aim the analytical expression of permanent displacement s given by Ambraseys (1995] could be useful:

$$\log(s) = -2.41 + 0.47\,M - 0.01\,r + \log[(1-\eta)^{2.64}(\eta)^{-1.02}] + 0.58\,p \qquad (6)$$

being M the magnitude of the earthquake, r ipocentral distance and p standard deviation of the assumed normal distribution.

Combining expressions (4) and (5) the maximum PGA acceleration $K_{max}$ that gives allowable permanent settlements can be expressed in terms of the ratio $\eta = \eta_a$:

$$K_{max} = [K_h (F_{so} - 1)] / [\eta_a (F_{so} - F_s)] \qquad (7)$$

According to the italian code (D.M. LL. PP.,1982) minimum values of the safety factors are $F_{so}=1.4$ (static condition, i.e. $K_h=0$) and $F_s=1.2$ for $K_h= K_{code}$ ($K_{code}=0.10$, 0.07 or 0.04 depending on the seismic zone classification). By substituting the above values in (7), we have:

$$K_{max} = 2\,K_{code} / \eta_a \qquad (8)$$

For the serviceability limit state a permanent displacement s of some millimeters may be tolerated for a moderate earthquake (the so-called OBE, Operating Basis Earthquake) and a value of $\eta_a=0.7$ is assumed (see Fig. 8); for the ultimate limit state (seismic load SEE, Safety Evaluation Earthquake) centimetric values of s can be hold as allowable ($\eta_a=0.5$). By adopting the above $\eta_a$ values in (8), respectively for the serviceability and the ultimate limit states, the PGA shown in Table III are obtained: the values suggest that a dam could face accelerations up to 3-4 times the constant level ones intro-

Tab. III – Peak Ground Acceleration values allowable for serviceability (OBE) and ultimate (SEE) limit states.

*Tab. III – Valori ammissibili del picco di accelerazione nelle condizioni di servizio (OBE) e di stato limite ultimo (SEE).*

| M=6 | Seismic zone | PGA (g) |
|---|---|---|
| OBE ($\eta_a=0.7$) | 1st ($K_{code}=0.10$) | 0.28 |
| | 2nd ($K_{code}=0.07$) | 0.20 |
| SSE ($\eta_a=0.5$) | 1st ($K_{code}=0.10$) | 0.40 |
| | 2nd ($K_{code}=0.07$) | 0.28 |

Tab. IV – Permanent displacements computed by several authors using statistical approach.
*Tab. IV – Spostamenti permanenti calcolati con dati statistici proposti da vari autori.*

UMBRIA-MARCHE EARTHQUAKE OF SEPTEMBER 26, 1997 (11:40 local time) Ms=5.9

| | | | | | | NEWMARK (1965) s=f(Kc,Kmax) | SARMA (1975) s=f(Kc,Kmax,To) | MAKDISI & SEED (1978) s=f(Kc,Kmax, To,M) | AMBRASEYS *et al.* (1995) s=f(Kc,Kmax, M,r) | CRESPELLANI *et al.* (1998) s=f(Kc,Kmax,Pd) |
|---|---|---|---|---|---|---|---|---|---|---|
| Records | Slope | zone | Kc | Kmax | Kc/Kmax | $s_{max}$ (cm) | $s_{max}$ (cm) | $s_{max}$ (cm) | $s_{\sigma}$ (cm) | $s_{90}$ (cm) |
| RA01168 (Nocera Umbra) PGA=0.56 g; Arias Int. =335 (cm/s); Pd =1.49 (cm s) | downstream & upstrem | upper | 0.08 | 0.56 | 0.14 | 250.0 | 17.4 | 37.1 | 43.2 | 20.2 |
| | upstream | medium | 0.15 | 0.56 | 0.27 | 80.0 | 8.3 | 10.7 | 15.0 | 10.6 |
| | downstream | medium | 0.175 | 0.56 | 0.31 | 62.5 | 5.8 | 6.4 | 10.9 | 9.1 |
| | upstream | lower | 0.22 | 0.56 | 0.39 | 40.0 | 2.1 | 3.4 | 6.2 | 7.2 |
| | downstream | lower | 0.25 | 0.56 | 0.45 | 27.5 | 1.3 | 2.6 | 4.3 | 6.3 |
| RA01156 (Colfiorito) PGA=0.28 g; Arias Int. =46.5 (cm/s); Pd=0.2 (cm s) | downstream & upstrem | upper | 0.08 | 0.28 | 0.29 | 75.0 | 3.8 | 5.7 | 10.2 | 2.8 |
| | upstream | medium | 0.15 | 0.28 | 0.54 | 15.0 | 0.3 | 0.9 | 1.7 | 1.5 |
| | downstream | medium | 0.175 | 0.28 | 0.63 | 15.0 | 0.2 | 0.4 | 0.8 | 1.3 |
| | upstream | lower | 0.22 | 0.28 | 0.79 | 10.0 | 0.1 | 0.7 | 0.2 | 1.0 |
| | downstream | lower | 0.25 | 0.28 | 0.89 | 7.5 | 0.0 | 0.0 | 0.0 | 0.9 |

duced in the pseudo-static approach with permanent displacements within tolerable limits.

The above frame fits well with Acciano dam behaviour: in fact the upper part of the shells, that did not respect the code provisions in term of safety factor, have suffered deformations in excess and extensive cracking. Nevertheless global safety was never exposed to risk (at least for the reservoir level 504 m a.s.l.) in full agreement with the larger $F_s$ provided for the lower circles concerning the embankment and the foundation soil.

## 5. Conclusions

The permanent displacements and the cracking pattern of Acciano earth dam during the Umbria-Marche seismic sequence of September 1997 show, both in terms of absolute settlements and instability phenomena, values consistent with those predicted by semi-empirical relations. The other dams located at greater distances from the epicentres did not show significant damages.

Some general comments may be helpful to explain the observed evidences. First it must be pointed out the relevance of the accelerometric network, of primary importance in evaluating the level of inertia forces to which the structures have been exposed. Of course, the use of accelerometric records must account for possible local soil amplification. For large dams, located in zones of high seismic risk, the availability of in site accelerometric stations is essential for a closer analysis of soil-structure interaction effects. In these conditions, if also a detailed geotechnical characterization is available, more sophisticated procedures, such as non-linear dynamic analysis, may be adopted to reach a higher degree of approximation of the model.

As shown for the Acciano earth dam, simplified semi-empirical relations based on the original Newmark's method, are reliable in assessing permanent deformations when the effects of lose of strength due to cyclic loads or to pore pressure increase are negligible.

At last, as regards the pseudo-static method currently used in engineering evaluations, it has been pointed out that the respect of the safety factors required by the italian code let the structures to withstand acceleration levels considerably higher than the estabilished pseudo-static coefficients.

As pointed out, an earth dam could face peak ground accelerations of about 0.40 g and 0.28 g, for 1st and 2nd seismic zones respectively, with permanent deformations still allowable for safety limit state. Those PGA are 4 times the pseudo-static coefficient values fixed by the italian regulation.

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## Il comportamento della diga in terra di Acciano durante il terremoto umbro-marchigiano del settembre 1997

### *Sommario*

*Il terremoto che nel settembre del 1997 ha colpito le regioni Umbria e Marche è stato uno dei più forti registrati in Italia negli ultimi venti anni. La rete accelerometrica presente in varie postazioni nell'area epicentrale ha fatto registrare valori elevati di accelerazione, sino a 0.56 g a Nocera Umbra, ponendo in evidenza anche forti effetti di amplificazione locale. In prossimità di Nocera Umbra è ubicata la diga in terra, del tipo zonato, di Acciano, che ha manifestato danni al coronamento consistenti principalmente in un'estesa fessurazione longitudinale e in spostamenti che hanno raggiunto valori massimi di circa 10 e 20 centimetri, rispettivamente nella direzione monte-valle e verticale. Nell'articolo viene esaminato il comportamento dinamico della diga, applicando il metodo di calcolo originariamente proposto da Newmark e sono posti a confronto gli spostamenti calcolati e quelli osservati. Infine si correlano i fattori di sicurezza, derivanti dall'applicazione dell'usuale metodo pseudo-statico, con gli spostamenti permanenti da ritenersi ammissibili ai fini di sicurezza e della funzionalità dell'opera. L'esperimento in "vera scala fatto dalla Natura", nel confermare la validità del metodo di Newmark nella valutazione dei cedimenti, mostra che il rispetto dei coefficienti di sicurezza minimi previsti dalla normativa assicura una risposta accettabile, in termini di spostamenti permanenti, per valori di picco dell'accelerazione fino a 3-4 volte quelli previsti con l'approccio pseudo-statico.*