The grade-2 microzonation of Sellano

Maria Rossella Massimino*, Michele Maugeri**, Silvio Zuccarello**

Summary
The seismic sequence, which occurred in the Umbria and Marche Regions in 1997-1998, even if it was characterised by quite moderate magnitudes, caused significant damage to buildings and determined the failure of many slopes. This event underlines once more the necessity to zone all the Italian seismic areas in relation to the seismic site amplification, landslide and liquefaction phenomena.

The paper presents the seismic site amplification hazard maps and the seismic landslide hazard maps for the town of Sellano (Umbria) and its surrounding villages. The procedures utilised to draw these maps come from the Augusti et al. [1985, 1988] studies as regards the seismic site amplification hazard and from the Maugeri et al. [1994] studies as regards the seismic landslide hazard. Moreover, these procedures follow the guidelines suggested in the Manual for Zonation on Seismic Geotechnical Hazards [TC4, 1999] and allow a Grade-2 microzonation level to be achieved.

1. Introduction

The Italian seismic law in force [D. M. 16 January 1996], that establishes the characteristics of new constructions in Italian seismic areas, does not represent an adequate tool to overcome the seismic risk, because it does not take sufficiently into account the possible local amplification phenomena of the ground motion, nor other geotechnical phenomena, such as landslides or liquefaction. However, the necessity to seismically improve or retrofit the existing buildings is becoming more and more urgent, as is the necessity to protect buildings, facilities and lifelines from landslides and liquefaction.

The present paper shows the seismic site amplification hazard zonation of Sellano and its surrounding villages of Forfi, Petrognano, Piagia, Villamagna and Vio, seriously damaged between September 1997 and April 1998. The zonation is developed taking into consideration the guidelines reported in the "Manual for Zonation on Seismic Geotechnical Hazards", prepared in 1993 by the TC4 of ISSMGE and republished in 1999 by the Japanese Society of Soil Mechanics and Foundation Engineering [TC4, 1999].

The seismic site amplification hazard is evaluated by means of a semi-quantitative procedure, founded on the calculation of a hazard index. The latter is defined on the basis of the investigated geological, geomorphologic and geotechnical characteristics.

Furthermore, coming from the evaluation of the seismic, geomorphologic and geotechnical nature of Sellano and the surrounding villages above mentioned, including in this case also Petrognano, the areas potentially subjected to seismic slope instability are identified. As far as the liquefaction is concerned, liquefaction phenomena were not observed because, as will be mentioned in paragraph 2, the ground consists mainly of silty-clayey debris.

Considering that the aim of a seismic geotechnical hazard zonation consists of the elaboration of thematic maps, useful for more rational town-planning, the seismic site amplification and slope instability hazard maps are drawn up for the area of Sellano and for its surrounding villages.

2. The Umbria-Marche seismic sequence of 1997-1998

The seismic sequence of 1997-1998 fits very well with the seismic, historical scenery of the Umbria and Marche Regions [Monachesi et al., 1997; Cermis et al., 1998]. In particular, the seismic sequence of 1997-1998 was characterised by magnitude values very close to those of the strongest seismic events that had previously occurred in the Apennines. This event caused non-negligible damage in different areas of the Umbria and Marche Regions. Significant site amplification phenomena occurred at great distances from the epicentral areas [Massimino et al., 2000]. The 1997-1998 sequence started on 3 September 1997 (at 22:07 GMT) with a shock of magnitude $M_L = 4.5$ and the epicentre in the area of Colfiorito. This shock was followed by other different shocks of lower magnitude. However, the first significant shock was that of 26 September 1997 at 00:33 GMT of $M_L = 5.5$ and the same localisation as the previous one. This last shock caused extensive damage at Colfiorito, Colle-

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curti and Cesi. On the same day another strong
shock took place at 09:40 GMT, with a magnitude
$M_L = 5.8$ [GAMASSI et al., 1997]. The following
seismic activity involved mainly the area that extends
from Sellano to Nocera Umbra. In particular, on 6
October 1997 (23:24 GMT) a shock of $M_L = 5.3$
hit the zone of Casenove, near Colfiorito. The last very
significant shock ($M_L = 5.4$) occurred on 14 Octo-
ber 1997 (15:23 GMT) near to Preci and Sellano
[BOSCHI et al., 1997; Decanini et al., 1999]. Due to
this latter event a very high level of damage occurred
in Sellano.

3. Site conditions

The area of Sellano and its surrounding villages
are reported in Fig. 1. The town of Sellano is located
640 m above sea level in the centre of the Umbria
Region. The old centre is in proximity to the eastern
boundary of an Ante-Apennines ridge. In the whole
built-up area some soil formations, typical of the Ap-
ennines of the Umbria and Marche Regions, have
been found. The latter are characterised by red, white,
grey-green and dark-grey stratified limestones, known respectively as Scaglia Rossa, Scaglia
Bianca, Scaglia Variegata and/or Scaglia Cinerea and
Biscaro [GUADAGNO et al., this issue]. The superficial
sheet consists of silty-clayey debris of fluvial origin
and of sld masses resulting from active and quiescent
landslide movements, that have involved the rock
substratum. Moreover, human activity has deeply
modified the primary morphologic configuration of
the built-up centre, principally through the excavati-
on and filling operations consequent from the forti-
fication of Sellano. This town was one of the most im-
portant “strong-holds” of the Spoleto area in the me-
dieval period. These factors have determined the
complexity of the Sellano subsoil, so it is very difficult
to schematise the geological and geotechnical fea-
tures of the foundation soil immediately underneath
the existing masonry structures. In any case, this soil
is characterised by moderate thickness and poor
static and dynamic geotechnical properties.

During the recent seismic events the presence of
the superficial debris sheet determined local seismic
amplification phenomena, that caused heavy dam-
age to the masonry buildings [DOLCE et al., this is-
ue]. In particular, in Fig. 2 it is possible to see the
damage that occurred in a masonry building located
in the village of Vio, near Sellano.

As far as the morphological aspects are con-
cerned, the whole area of the built-up centre was
subjected to strong fracturing phenomena and
landslide movements, which occurred numerous-
in consequence of the seismic sequence of 1997-
1998. Cracks, of limited extension and spread of
millimetres and/or centimetres, followed the isoseis-
mal trend. They became wider in the epicentre area
and smaller going away from the epicentre. Land-

Fig. 1 - Location of the analysed areas.
Fig. 1 - Ubicazione delle località oggetto di studio.

Fig. 2 - Example of structural damage (Vio Village).
Fig. 2 - Esempio di danno strutturale (Vio).
slide movements involved mainly the limestone and the stratified limestone-marl soil, showing predominantly debris flow or slip mechanisms. These events caused a lot of damage: many roads were partially or completely obstructed, several retaining walls were destroyed, and different buildings were damaged. In particular, a landslide caused the destruction of many buildings and roads in the village of Postignano (Fig. 3).

In consequence of the seismic event of 1997-1998, different studies were performed to characterise the geotechnical nature of the subsoil of the whole Sellano area and its villages of Forfi, Petrognano, Piaggia, Villamagina and Vio. Boreholes, standard penetration tests, D-H tests, measurements of water level by means of piezometers and measurements of horizontal soil displacements by means of inclinometers were performed. Moreover, numerous specimens, taken during the perforations, were submitted to laboratory geotechnical tests. Standard equipment was used to perform geotechnical tests. The results obtained by in-situ and laboratory tests are reported by Cavallaro et al. [this issue].

In particular, for the site characterisation of the ground of Sellano thirteen boreholes were carried out. During the perforation six D-H tests, three piezometer tests and seven inclinometer tests were also carried out (Fig. 4). Analysing the results of these geotechnical tests, it is possible to individuate the following strata, starting from the soil surface. The first stratum consists of filling soil with a prevalently clay component. This stratum has a depth variable from 0.8 m (borehole S5) to about 10.0 m in proximity to the area around the old centre (borehole S4). Then, a stratum of plastic clay with limestone inclusions of variable size follows. The depth of this second stratum changes from a minimum value of 1.5 m (borehole S5) to a maximum value of 12.5 m (borehole S1). Finally a layer of limestone marl with high clay content and marly limestone was found. It must also be underlined that along the boreholes named S4 and S7 the second clay stratum is not present; thus the third stratum, mentioned above, follows the first one. The laboratory tests on specimens taken from the superficial stratum, confirm the clay nature of this latter. In particular, the values of both the plasticity index \( I_p \), changing in the range of 6.0 \( \pm \)17.2 %, and the consistent index \( I_c \), changing in the range of 0.6 \( \pm \)1.5, prove the presence of superficial clay with a quite plastic-solid behaviour. Moreover, utilising the results of the D-H tests performed in the boreholes named S3, S4, S7, S8, S11 and S13, it is possible to determine the shear wave velocity \( V_s \) versus the depth \( z \). For the boreholes without D-H tests the \( V_s \) trend is estimated on the basis of the comparison of the information coming from all the boreholes.

As far as the groundwater level is concerned, it is near the surface in borehole S2 and it is at a depth of 5.0 m in borehole S5, located outside the Sellano built-up area (Fig. 4); in the other boreholes the groundwater was not observed.

Other boreholes were performed in the surrounding villages (see figures mentioned in paragraph 6.3). More precisely, the following in-situ investigations were performed: two boreholes (one with D-H test) at Forfi, three boreholes (two with D-H tests) at Petrognano, five boreholes (two with D-H tests and three with SPT tests) at Piaggia, four boreholes (three with SPT tests) at Villamagina, three boreholes (two with D-H tests) at Vio and nine boreholes at Postignano. The subsoil of Forfi is mainly characterised by outcropping debris of great depth. This latter is equal to 11.0 m in borehole S1, while reaching 27.0 m in borehole S2. This situation can be a cause of a high seismic hazard, due to the possible high value of the seismic wave amplification in this kind of soil. In the village of Petrognano the superficial layer of filling and debris has a minor depth, variable from 1.0 m (borehole S1) to 4.3 m (borehole S3). Then, the Scaglia Variegata is present. Only in borehole S3 at the depth of about 10.0 m the Scaglia Rossata follows the above Scaglia Variegata. For the village of Piaggia it is possible to underline a non-negligible difference between the soil profile in the urban centre and the soil profile in the valley-bottom. The first profile is characterised by an outcropping layer, about 3.0 m thick, of gravelly-sandy clay (boreholes S1 and S2); the second profile is characterised by soft soil with very poor properties up to a great depth, that justifies the recognised heavy damage. In Villamagina, starting from the soil surface, it is possible to note a first, very thin, layer of filling and vegetal soil. Then some gravel layers with different clay contents are present up to the depth of about 6.0 m. At the above depth the layer of Scaglia Bianca starts. The subsoil of Vio is mainly constituted by a first layer of debris, with a thickness variable from 4.5 m (borehole S1) to 10.7

Fig. 3 - Example of landslide occurred at Postignano Village
Fig. 3 - Esempio di frana avvenuta a Postignano.
m (borehole S2) and a second layer of Scaglia Cine-rea. Finally, at Postignano there are limestone debris layers mixed with clay layers then, at a depth of about 12-15 m (6.0 m only in borehole S2), a rock formation follows. As far as the groundwater is concerned, it was found only in borehole S3 of Petignano at the depth of 6.2 m, in boreholes S1, S2, S4, S6 and S7 of Postignano respectively at the depth of 10.5 m, 5.9 m, 13.5 m, 6.2 m and 3.0 m, and in borehole S2 of Vio at the depth of 9.8 m.

4. Zonation of Geotechnical Earthquake Hazards

4.1. General

Building protection against earthquakes must be carried out in two directions: the earthquake effects in the soil, such as local amplification, landsliding and liquefaction, must be analysed; the structural safety against dynamic horizontal forces induced by seismic events must be guaranteed. Then to predict the seismic risk of a given area the seismic geotechnical hazard zonation of this area must be carried out drawing thematic maps, which should support the town-planning and structural projects.

The Manual for Zonation on Seismic Geotechnical Hazards [TC4, 1999] describes three zonation grades and regards three different geotechnical phenomena induced by earthquakes: the local ground response, the seismic slope instability and the liquefaction.

Grade 1 is based on the collecting of information available in literature and in historical documentation. This approach is the simplest and the lowest-cost; so it is used to analyse very large areas. In this level of analysis it is possible to take into consideration the historical earthquakes and eventually the registrations of recent earthquakes, their epicentre, magnitude and focal mechanism. Geological data regarding active faults are also collected. The seismological and geological data are useful for the allocation of hypothetical earthquakes and the evaluation of the return period. The zonation maps are generally drawn on the scale of 1:1.000.000 or 1 to 50.000. Thus, it is a "general zonation".

Grade 2 improves the previous zonation, increasing the amount and typology of information without significantly increasing the costs. To better define the geological and fault conditions, aerial photographs, old photographs, additional field studies, geotechnical engineering reports and microtremor measurements are useful additional tools. Standard geotechnical in-situ and laboratory investigations are also carried out. Specific maps to scales of 1:100.000 to 1:10.000 are prepared, reaching a "detailed zonation".

In Grade 3 a "rigorous zonation", in more detailed scales of 1:25.000 to 1:5.000, is achieved. In this last case additional specific site investigations are very often necessary. It considerably increases the costs; but in some areas, characterised by a very high seismic risk, this rigorous zonation is necessary to guarantee the safety of structures and facilities.

The next paragraphs report only the general criteria for the evaluation of the local site effect due
to the ground motion amplification and the slope instability hazard, considering that for the whole area of Sellano liquefaction phenomena did not occur.

4.2. Ground motion amplification

The analysis of the ground motion and of the possible seismic wave amplification approaching the soil surface is one of the fundamental aspects for the assessment of the seismic hazard. This factor can be the cause of great structural damage, being closely linked to the seismic horizontal forces acting on structures and causing serious soil failures.

The ground motion assessment depends on: 1) the regional seismicity; 2) the attenuation of ground motion intensity; 3) the local site effects. The latter are closely related to the evaluation of the surface ground motion amplification. Then, in the above mentioned manual, three different levels of analysis are considered for these special effects.

As far as the local site effects are concerned, under Grade-1 level they are evaluated by means of the existing information available from published data, considering for example the distribution of damage induced by the past earthquakes, the isoseismic maps, statistical analyses based on the compilation of specific questionnaires to estimate the seismic intensity and empirical correlation between surface geology and seismic intensity increment [Astroza et al., 1991].

Grade-2 approaches require more soil information than Grade-1 approaches to better evaluate the geotechnical properties of the analysed sites. To achieve this information standard geotechnical investigations, ground classification data and microtremor measurements must be taken into account. The in-situ geotechnical investigations, such as the Standard Penetration tests and the Cone Penetration Tests, allow, by means of empirical correlations [Robertson et al., 1983], the estimation of the shear wave velocity and its variation with depth. Finally on the basis of the microtremor measurements it is also possible to achieve indirect information on the geotechnical dynamic properties. The Grade-2 approaches are generally based on score and penalty procedures.

The most important methods for the evaluation of seismic site amplification are part of the Grade-3 level and are based on specific geotechnical in-situ investigations, such as D-H tests and C-H tests, and specific laboratory geotechnical investigations, such as the resonant column tests and the cyclic loading torsional shear tests, which allow the analysis of the variation of the shear modulus and damping ratio with the shear strain level. Mono-dimensional soil modelling in linear or non-linear conditions, such as that used in Capilleri et al. [this issue], and recently two- and three-dimensional soil modelling are utilised at this level of microzonation.

The zonation for seismic site amplification for Sellano and its surrounding villages, reported in paragraph 5, even if it is based on the available D-H test results, can be considered a Grade-2 zonation.

4.3. Slope instability

When an earthquake occurs one of the major indirect causes of structural damage comes from the collapse of slopes located next to built-up areas. Several buildings were destroyed in the past due to seismic slope collapse [Crespelani et al., 1996], and some towns and villages were submerged. Consequently, the evaluation of the slope instability hazard is one of the most important aspects of the task of seismic zonation [Jibson et al., 1998; Keefer et al., 1998]. Even during the recent Umbria-Marche seismic sequence of 1997-1998 some areas of this part of Italy were subjected to dangerous seismic slope instabilities.

The microzonation for slope instability can be characterised by different approaches with an increase in accuracy and reliability: the statistical elaboration (Grade-1) of the occurred-landslide data [Ishihara et al., 1987; Chierico et al., 1999], the score and penalty procedures (Grade-2) and the more sophisticated deterministic approaches (Grade-3).

In the Manual for Zonation on Seismic Geotechnical Hazards [TC4, 1999] two factors are pointed out as the mean factors for slope instability: the external forces and the soil resistance to movement. The external forces consist in gravitational and seismic forces; the soil resistance is based essentially on the geological and geotechnical conditions. Different methods have been developed to estimate the influence of these factors. These methods are based on the limit equilibrium analysis and do not take into account the displacement aspect. Furthermore, other methods have been developed on the basis of the Newmark [1965] sliding block model, which perform substantially pseudo-dynamic and/or displacement analysis [Crespelani et al., 1990; 1996; Kramer et al., 1997; Crespelani et al., 1998]. More recently, FEM, BEM and FDM methods are being utilised more and more [Griffiths, 1996; Tabesh et al., 1997; Chowdhury et al., 1998; Yu et al., 1998] due to their power for modelling complex slope geometries and properties, including elasto-plastic and/or elasto-viscoplastic constitutive laws with associated and/or non-associated flow rules.
However, it is often very difficult to correctly apply all these methods, because they need detailed information, while frequently the available geological, geomorphologic and geotechnical data are very poor and do not cover the whole examined area. Moreover, in some cases particular phenomena, such as the shear strength degradation [Cascone et al., 1998], the seismic induced pore water pressure and the liquefaction [Biondo et al., 2000a; 2000b], can play the main role in the slope instability. Finally, it is very rare to have strong motion records in the site or in the surroundings.

Because detailed information is not available for Sellano and its surrounding villages, the microzonation for slope instability reported in paragraph 6 can be considered a Grade-2 microzonation, according to TC4 [1999].

5. Evaluation and microzonation of seismic site amplification

5.1. General procedure

The compilation of seismic site amplification maps should be the first step for the seismic risk evaluation [Marcellini et al., this issue]. Following the general criteria given by TC4 [1999] for Grade-2 microzonation, the semi-quantitative procedure introduced by Augusti et al. [1985, 1988] is used in the present paper. This procedure is based on the filling of a Penalty Form, adapted to the geomorphologic and geologic features of the Umbria zones. This procedure was successfully used by Crespellani et al. [1987] and by Crespellani and Garronzo [1996] for the city of Gubbio and by Cascone et al. [1997, 1999] for the city of Catania. The formulation criteria of the Penalty Form have been improved since the first studies of Augusti et al. [1985; 1988] on the basis of the experimental observations regarding the damage that occurred and the geological and geotechnical conditions of the investigated areas.

In particular, in the present paper the last version of the Penalty Form reported in Cascone et al. [1999] is utilized, with some modifications, above all, on the shear wave velocity values, according to the new ECB [2000]. The general Penalty Form reported in Cascone et al. [1999] considers the following factors: the shear wave velocity versus the soil depth, the contrast of the shear wave velocity, the cyclic degradation of resistance, the distance from lithological discontinuities, the distance from active faults, the presence of cavities, the overall morphology, the local slope angle, the landslide phenomena, the water table depth and the susceptibility to liquefaction.

In the present application of this form two points must be stressed. First: the general Penalty Form leads to a comprehensive seismic hazard evaluation, concerning not only the site amplification phenomena, but also the seismic landslide and liquefaction phenomena. In the present work the Penalty Form is used only to evaluate the seismic hazard at the site amplification phenomena. Thus in the Penalty Form reported in Tab. 1 the landslide and liquefaction phenomena, included in the general form, are not present. The landslide phenomena are analysed separately in paragraph 6. Liquefaction phenomena, as previously mentioned, do not occur in Sellano and its surrounding villages. Second: the general Penalty Form has validity for any kind of site condition, so for each situation some factors can be ignored. In particular, the Penalty Form utilized for Sellano and its surrounding villages does not include the following factors: the lateral discontinuities, the active faults and the cavities, apart from the landslide and liquefaction phenomena above mentioned.

The factors taken into account in the utilized Penalty Form (Tab. 1) are reported below. The penalties, linked to each factor, are fixed as shown in Tab. 1 and according to the following criteria.

Shear wave velocity $V_s$ versus soil depth $z$.

The greater the shear wave velocity the stiffer the soil, and consequently less ground motion modifications, in terms of amplification and frequency content, occur. Then, the $V_s$-$z$ distribution represents the most important geotechnical factor to characterize the soil stratigraphy in dynamic conditions. On the basis of the $V_s$ values, the soil can be subdivided in: stiff soil, medium soil and soft soil. It must be stressed that in the present paper the ranges of the $V_s$ values suggested by the new ECB [2000] are taken into account instead of the ranges reported in Cascone et al. [1999]. Then, the stiff soil is defined by $V_s > 360$ m/s; the medium soil by $180 < V_s < 360$ m/s and the soft soil by $V_s < 180$ m/s. For $V_s > 360$ m/s the penalty $P(V_s)$ is fixed equal to 0.5 for every soil depth $H$ in the range of 0 $\div$ 90 m; for $180 < V_s < 360$ m/s in the soil depth $H$ of 0 $\div$ 15 m $P(V_s)$ is fixed equal to 1.5 when $180 < V_s < 240$ m/s, to 1 when $240 < V_s < 300$ m/s and to 0.5 when $300 < V_s < 360$ m/s and some thin moderately soft layers exist. Similarly, for $V_s < 180$ m/s and $H = 0 \div 90$ m, $P(V_s)$ is fixed equal to the maximum or the minimum value reported in Tab. 1, respectively for $V_s < 100$ m/s and for $100 < V_s < 180$ m/s. In the other cases the utilised penalties correspond to the maximum values suggested by Cascone et al. [1999]. The conventional bedrock is fixed at a depth where $V_s \geq 800$ m/s, according to ECB [2000].
### Penalties

<table>
<thead>
<tr>
<th>SUBSOIL PARAMETERS</th>
<th>PENALTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>TYPE OF SOIL</td>
<td>LOW</td>
</tr>
<tr>
<td>SHEAR WAVE VELOCITY</td>
<td>STIFF SOIL</td>
</tr>
<tr>
<td>DEPTH [m] 0 - 5</td>
<td>$V_s &gt; 360$ m/s</td>
</tr>
<tr>
<td>5 - 15</td>
<td>0.5</td>
</tr>
<tr>
<td>15 - 30</td>
<td>0.5</td>
</tr>
<tr>
<td>30 - 90</td>
<td>0.5</td>
</tr>
<tr>
<td>CONTRAST OF SHEAR WAVE VELOCITY</td>
<td>$\Delta V_s &lt; 180$ m/s</td>
</tr>
<tr>
<td>DEPTH [m] 0 - 10</td>
<td>1 - 2</td>
</tr>
<tr>
<td>10 - 30</td>
<td>0.5 - 1</td>
</tr>
<tr>
<td>30 - 90</td>
<td>0 - 0.5</td>
</tr>
<tr>
<td>CYCLIC DEGRADATION OF RESISTANCE</td>
<td>$I_p &gt; 50$</td>
</tr>
<tr>
<td>WATER TABLE DEPTH</td>
<td>$d &gt; 10$ m</td>
</tr>
<tr>
<td>OVERALL MORPHOLOGY</td>
<td>Flat area</td>
</tr>
<tr>
<td>LOCAL SLOPE ANGLE</td>
<td>$i &lt; 5^\circ$</td>
</tr>
</tbody>
</table>

**Contrast of the shear wave velocity $\Delta V_s$.** The entity of shear wave velocity contrast and the depth at which this contrast is located can change significantly the strain-stress level due to an earthquake, as well as the natural vibration period of the soil, leading to great amplification phenomena. Then, for $\Delta V_s > 360$ m/s $P(\Delta V_s) = 3$ is chosen when the velocity contrast is located at the depth $H = 0 \div 30$ m, while $P(\Delta V_s) = 2$ is chosen when the velocity contrast is located at the depth $H = 30 \div 90$ m. In the other cases ($180 < \Delta V_s < 360$ m/s and $\Delta V_s < 180$ m/s) the penalty is evaluated inside the range given in Tab. I.

**Cyclic degradation of resistance.** This factor could be associated to the plasticity index $I_p$, considering that it has been proved experimentally [BAN et al., 1989] that the cyclic shear strength degradation increases with the decrease of $I_p$. The analysed soil is characterised by a medium plasticity, then in the **Penalty Form** the penalty value of 0 is fixed for $I_p > 50$, the penalty value of 1 is fixed for $20 < I_p < 50$, the penalty value of 2 is fixed for $10 < I_p < 20$ and for a new category of $I_p < 10$ a penalty value of 3 is fixed. The case of $I_p < 10$, not taken into account in the **Penalty Form** of CASCONE et al. [1999], was found for some small examined areas.

**Water table depth.** The penalty due to the ground water, considered up to a depth of 10 m, increases as the depth decreases, according to CASCONE et al. [1999], to take into account the decrease of the effective stresses near the foundation level.

**Overall morphology and local slope angle.** These factors take into account the effects of the topographic conditions on possible ground motion amplification. The average values among those reported by CASCONE et al. [1999] are considered (Tab. I).

The sum of the potential penalties gives a geotechnical hazard index $I_{GH}$, which is related only to site amplification phenomena.

The values of $I_{GH}$ are grouped in five different ranges corresponding to a site amplification hazard from low to very high (Tab. II).

On the basis of this semi-quantitative procedure the evaluation of the geotechnical hazard index $I_{GH}$, is made for the town of Sellano (see paragraph 5.2) and for its surrounding villages (see paragraph 5.3).

Finally, the damage observed just after the seismic sequence of 1997-1998 is considered and compared with the $I_{GH}$ microzonation maps. As an example, this comparison is reported in the next paragraph only for the town of Sellano. However, both for Sellano and its surrounding villages, a good
agreement is found between the $I_{GH}$ evaluation and the damage observed.

5.2. The $I_{GH}$ microzonation of the town of Sellano

Analysing the different boreholes made in Sellano, as well as in its surrounding villages, it is possible to note that the most important layers for the evaluation of the site amplification are over the depth of 25 m. At this depth it is possible to locate a stiffer layer on which the upper softer soil rests. However, considering that generally the first 90 m from the soil surface are considered subject to possible amplification phenomena, it is the depth of 90 m that is considered in this case. Moreover, to take into account the soil stratigraphy, some very thin layers are ignored [Cavallaro et al., this issue].

The microzonation map of the site amplification hazard of the town of Sellano is reported in Fig. 5. This map is carried out on the basis of the geological information coming from the above mentioned boreholes S4, S6, S7, S8, S9, S10, S11 and S13, the geological map reported in Guadagno et al. [this issue] and on other information collected during a 1998 survey. In this case, the site amplification is very significant and, in particular, the levels reached are IV and V, corresponding to the high and very high site amplification hazards respectively. Level V ($I_{GH} > 10.5$) is reached inside the Scaglia Varegata formation. Level IV is reached in a wide area characterised by the Scaglia Cenere and the Bis-

<table>
<thead>
<tr>
<th>$I_{GH}$</th>
<th>SITE AMPLIFICATION HAZARD</th>
<th>LEVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 + 4.0</td>
<td>Low</td>
<td>I</td>
</tr>
<tr>
<td>4.5 + 6.0</td>
<td>Moderate</td>
<td>II</td>
</tr>
<tr>
<td>6.5 + 8.0</td>
<td>Medium</td>
<td>III</td>
</tr>
<tr>
<td>8.5 + 10.0</td>
<td>High</td>
<td>IV</td>
</tr>
<tr>
<td>$&gt; 10.5$</td>
<td>Very high</td>
<td>V</td>
</tr>
</tbody>
</table>

ciaro formations. This area is subdivided by means of a conventional boundary into two sub-areas: the left sub-area is characterised by $I_{GH} = 8.5$, the right one is characterised by $I_{GH} = 10$.

The $I_{GH}$ microzonation map of Fig. 5 agrees very well with the map of the damage reported in Fig. 6 and in Dolce et al. [this issue], corroborating once more the validity of the utilised procedure even for the investigated zones. Sellano suffered great damage during the recent earthquake sequence, above all in the old centre [Guadagno et al., this issue], due to the greater building vulnerability [Dolce et al., this issue] and the greater seismic site amplification. On the basis of a local survey of different R/C and masonry buildings of Sellano the damage map reported in Fig. 6 is drawn. In this figure it is possible to note two different areas: the left one characterised by low-moderate

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Fig. 5 – Local seismic site amplification hazard map for the town of Sellano.
Fig. 5 – Mappa di pericolosità per fenomeni di amplificazione sismica locale per la città di Sellano.
damage and the right one, characterised by high damage. The last area corresponds to the old centre of Sellano.

This agreement, between the estimated site amplification hazard level and the observed building damage, can also be noted from Tab. III, where for each building reported in Fig. 6 the observed damage is compared with the $I_{GH}$ value determined for the nearest boreholes. In any case it must be underlined that the damage occurred can also be linked to the building vulnerability so, apart from the site amplification, the R/C frame buildings showed non-remarkable – low damage, while the masonry buildings showed low – severe damage.

5.3. The $I_{GH}$ microzonation of the surrounding villages

Following the procedure utilised for the town of Sellano, the microzonation maps of the seismic site amplification hazard for the surrounding villages of Sellano are reported in Figs. 7-11. For Forli (Fig. 7) the site amplification hazard is very high, reaching level V. At Petrognano (Fig. 8) the site amplification hazard is high, reaching level IV. For Piaggia (Fig. 9) the site amplification hazard is moderate, corresponding to level II. For Villamagna (Fig. 10) the site amplification hazard is medium, corresponding to level III. A moderate site amplification hazard of level II is evaluated for Vio (Fig. 11). Considering that the major damage to Postignano was due to a landslide (see paragraph

<table>
<thead>
<tr>
<th>Building</th>
<th>Typology</th>
<th>Damage</th>
<th>$I_{GH}$</th>
<th>Site amplification hazard</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>masonry</td>
<td>severe</td>
<td>11.0</td>
<td>very high</td>
</tr>
<tr>
<td>2</td>
<td>masonry</td>
<td>severe</td>
<td>11.0</td>
<td>very high</td>
</tr>
<tr>
<td>3</td>
<td>masonry</td>
<td>severe</td>
<td>11.0</td>
<td>very high</td>
</tr>
<tr>
<td>4</td>
<td>masonry</td>
<td>severe</td>
<td>10.0</td>
<td>high</td>
</tr>
<tr>
<td>5</td>
<td>masonry</td>
<td>low</td>
<td>10.0</td>
<td>high</td>
</tr>
<tr>
<td>6</td>
<td>masonry</td>
<td>low</td>
<td>10.0</td>
<td>high</td>
</tr>
<tr>
<td>7</td>
<td>masonry</td>
<td>severe</td>
<td>10.0</td>
<td>high</td>
</tr>
<tr>
<td>8</td>
<td>masonry</td>
<td>severe</td>
<td>11.0</td>
<td>very high</td>
</tr>
<tr>
<td>9</td>
<td>masonry</td>
<td>severe</td>
<td>11.0</td>
<td>very high</td>
</tr>
<tr>
<td>10</td>
<td>masonry</td>
<td>severe</td>
<td>11.0</td>
<td>very high</td>
</tr>
<tr>
<td>11</td>
<td>R/C frame</td>
<td>low</td>
<td>11.0</td>
<td>very high</td>
</tr>
<tr>
<td>12</td>
<td>masonry</td>
<td>severe</td>
<td>10.0</td>
<td>high</td>
</tr>
<tr>
<td>13</td>
<td>masonry</td>
<td>severe</td>
<td>10.0</td>
<td>high</td>
</tr>
<tr>
<td>14</td>
<td>masonry</td>
<td>severe</td>
<td>10.0</td>
<td>high</td>
</tr>
<tr>
<td>15</td>
<td>masonry</td>
<td>moderate</td>
<td>8.5</td>
<td>high</td>
</tr>
<tr>
<td>16</td>
<td>masonry</td>
<td>moderate</td>
<td>8.5</td>
<td>high</td>
</tr>
<tr>
<td>17</td>
<td>R/C frame</td>
<td>no-remarkable</td>
<td>8.5</td>
<td>high</td>
</tr>
<tr>
<td>18</td>
<td>R/C frame</td>
<td>no-remarkable</td>
<td>8.5</td>
<td>high</td>
</tr>
<tr>
<td>19</td>
<td>masonry</td>
<td>moderate</td>
<td>8.5</td>
<td>high</td>
</tr>
<tr>
<td>20</td>
<td>masonry</td>
<td>severe</td>
<td>8.5</td>
<td>high</td>
</tr>
<tr>
<td>21</td>
<td>R/C frame</td>
<td>no-remarkable</td>
<td>8.5</td>
<td>high</td>
</tr>
</tbody>
</table>
6), the site amplification phenomenon is not evaluated for this village.

The high values of the geotechnical hazard index found for Forfi and for Petrognano agree with the severe damage recognised for the buildings of these villages.

6. Evaluation and microzonation of slope instability

6.1. General procedure

The soil, as well known, can be subjected to seismic phenomena that can seriously compromise the stability of natural and man-made slopes and foundation subsoil [Civita et al., 1985; D'Elia, 1992; Ishihara et al., 2000; Yasuda, 2000]. The recognition of the areas characterised by active, quiescent or potential landslides is an incontrovertible help in preventing future landslides due to seismic events. In any case it is important to take into account that these phenomena are set off not always by the main shocks; very often, due to the latter, the slopes reach a condition near the limit equilibrium, then the next shocks, even of minor magnitude, produce the real landslide, because of cyclic strength degradation [Cascone et al., 1998].

To evaluate the stability conditions of a slope both the topographic maps regarding the whole area on which the slope lies and the local conditions of the considered slope must be taken into account. As far as the local conditions are concerned, one of the most important steps is the analysis of the possible local instabilities characterising the single slope. The latter can occur on the highest part of the slope, on the lowest part of the slope or along the sides of the slope. Generally, on the highest part of the slope (crown of the landslide) evident tension cracks are present, that allow the immediate localisation of the
failure surface. On the other hand, shallow-seated landslides and earthflow generate lateral ridges along the slope sides, due to the spreading out of the sliding soil material. Finally, the lowest part of the slope very often appears swollen and cracked [MAUGERI et al., 1982].

Moreover, to localise the failure more precisely boreholes must be performed up to a depth greater than the predicted failure depth. If necessary, some inclinometers, for measuring the different soil movements with the depth, can be installed.

Due to the seismic crisis that struck the Umbria-Marche area from September 1997 to April 1998, different slope instabilities showed. In particular, several falls, slumps and block slides occurred along the valleys characterised by a very high angle of slope, such as along the Vigi Valley, where it was necessary to close different parts of the SS209 road. Landslide phenomena also occurred in the villages. In particular, the village of Postignano was nearly covered by slide material (Fig. 3).

In consequence of these phenomena a specific investigation for the individuation of the areas susceptible to slope instability is carried out. The “Manual for Zonation on Seismic Geotechnical Hazards” [TC4, 1999] suggests, for the Grade-2 seismic slope instability zonation, procedures based on scores and penalties. According to these guidelines, a procedure developed by MAUGERI et al. [1994] is utilised in the present paper, considering the maximum epicentral distance of slope failure sites, the earthquake magnitude and the local site amplification. Secondly, the topography, geomorphology and physical properties of the soil, the environmental conditions of the slopes and the groundwater conditions are taken into account. The last factors characterise also the static stability of slopes and are connected to each other in the dynamic behaviour of each slope. The grade of static slope stability is very important to establish the seismic slope instability hazard [CHOWDHURY, 2000]. Both a critical static slope stability and a high regional seismicity must be present for the possible occurrence of a seismic landslide.

The application of the present procedure is also based on some unpublished information [BACCHI, 1998; BIGOZZI, 1998; CHERCUCI et al., 1998; CHIESI et al., 1998; LUCCHETTI et al., 1998; VAGATA, 1998a and 1998b], such as aerial photographs, geological and geotechnical reports, that are recognised as useful tools in achieving a good microzonation [HANSEN et al., 1991; YOUD, 1994].

As regards the seismic landslide phenomena, the very significant shock was the shock of 26 September 1997 at 00:33 [ESPOSITO et al., 2000]. In this case, the maximum epicentral distances of slope failure sites are the following: 12.1 km for Sellano, 9.0 km for Forfi, 12.3 km for Petrognano, 10.7 km
Tab. IV – Levels of seismic slope instability hazard. 

<table>
<thead>
<tr>
<th>Class</th>
<th>SEISMIC SLOPE HAZARD</th>
<th>LEVEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>High</td>
<td>IV</td>
</tr>
<tr>
<td>B</td>
<td>Medium</td>
<td>III</td>
</tr>
<tr>
<td>C</td>
<td>Moderate</td>
<td>II</td>
</tr>
<tr>
<td>D</td>
<td>Low</td>
<td>I</td>
</tr>
</tbody>
</table>

for Piaggia, 11.2 km for Villamagina, 10.2 km for Vio and 13.5 km for Postignano.

On the basis of the previous mentioned information, the seismic slope instability hazard is investigated for Sellano and its surrounding villages considering the four seismic slope hazard levels reported in Tab. IV.

6.2. The seismic slope instability microzonation of the town of Sellano

As it is possible to see in Fig. 12, in the built-up area of Sellano some slope instabilities of no great extension were localised above all around the old centre. The seismic slope hazard level is III, corresponding to a medium hazard. The instabilities are mainly of translation type and regard the mobilisation of talus masses. More details about these instabilities are reported in Guadagni et al. [this issue]. Besides, in an uninhabited area to the south of the town a high hazard is reached.

6.3. The seismic slope instability microzonation of the surrounding villages

Moving from the town of Sellano towards its surrounding villages, due to the morphological conditions, the slope instability hazard regards wide areas, reaching very high values in some critical zones. In particular, Forlì (Fig. 13) is for the most part characterised by a moderate slope instability hazard (level II); only in a small area a high hazard (level IV) is estimated. In the village of Petrognano (Fig. 14) the most critical levels III and IV (medium – high hazard) are reached in some small areas; then other wider areas are characterised by levels I and II (low – moderate hazard). For Piaggia (Fig. 15) the seismic slope instability problem is quite negligible: only in two areas of this village a moderate hazard (level II) is estimated. Villamagina and Vio (Figs. 16 and 17) are mainly characterised by a moderate hazard (level II); only in some small areas a medium hazard (level III) is reached. Postignano (Fig. 18) is certainly the Sellano village most greatly struck by slope instability during the last seismic sequence of 1997-1998. The whole area presents a moderate – high hazard. In particular, after the shock, which occurred at 00:33
FORFI

CLASS A
High seismic slope hazard

CLASS C
Moderate seismic slope hazard

Legend

Fig. 13 - Seismic slope instability hazard map for the village of Forfi.

PETROGNANO

CLASS A
High seismic slope hazard

CLASS B
Medium seismic slope hazard

CLASS C
Moderate seismic slope hazard

CLASS D
Low seismic slope hazard

Legend

Fig. 14 - Seismic slope instability hazard map for the village of Petrognano.

GMT of 26 September 1997, a very dangerous landslide took place to the north-east of the old centre (Fig. 3), causing the destruction of many buildings. This landslide was characterised by a slide mechanism in the lowest part of the slope and by block falls in the upper part. In consequence of the above shock and of the following shocks, some blocks of a volume bigger than 1.0 m³ reached the main road, causing a situation of very high risk for traffic.

Conclusions

The seismic microzonation of the town of Sellano and its surrounding villages points out very significant site amplification phenomena and a medium-high seismic landslide hazard. Liquefaction phenomena did not occur.

In particular, the site amplification map of Sellano, carried out from a semi-quantitative procedure, shows a high – very high site amplification
hazard. In the surrounding villages this hazard varies from moderate (Piaggia and Vio) to very high (Forfi). In any case the site amplification hazard evaluation agrees quite well with the observed damage level.

Then the reasons for the recognised high level of damage due to the quite moderate seismic sequence of 1997-1998, until now not completely clear, can be correlated to the significant estimated site amplification hazard and to the poor quality of a great number of the damaged buildings. The presence of soft soil near the soil surface, which represents quite frequently the foundation soil of the existing buildings, must be taken into consideration to explain such a great level of damage to the buildings.

As far as the seismic slope instability is concerned, the highest hazards are localised in a few villages around the town of Sellano and along the main roads, where different slopes were already in critical condition when the 1997-1998 seismic sequence occurred. The microzoning map of Postignano reports the highest hazard level, due to a wide landslide that covered a great part of the village during the seismic sequence. Because of critical static slope conditions a moderate shock triggered the collapse of many of them.
The developed maps, based on fast, repeatable procedures, less dependent on subjective judgment, can represent practical and very useful tools for the civil defence activities and the next steps of town-planning.

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References


Planning of Towns and regions in Seismic Prone Areas, Skopje, pp. 67-76.


Microzonaione di grado-2 per Sellano

Sommario:

La sequenza sismica verificatasi nell’Umbria e nelle Marche nel 1997-1998, sebbene sia stata caratterizzata da magnitudo alquanto moderata, ha causato danni significativi agli edifici ed ha scatenato l’instabilità di diversi pendii. Tali eventi sottolineano ancora una volta la necessità di zonare le aree sismiche del territorio italiano in relazione ai fenomeni sismici di amplificazione locale, instabilità e liquefazione.

Il presente articolo riporta le mappe di pericolosità relative ai fenomeni di amplificazione sismica locale ed instabilità sismica per la città di Sellano (Umbria) e le frazioni a questa appartenenti. Le procedure utilizzate per la realizzazione delle diverse mappe derivano dagli studi di Augusti et al. (1985; 1988) per quel che attiene al pericolo di amplificazione sismica locale e dagli studi di Maugeri et al. (1994) per quel che riguarda il pericolo di frane indotte da sisma. In ogni caso, tali procedure seguono le linee guida riportate nel “Manuale per la Microzonaione della Pericolosità Sismica Geotecnica” [TCA, 1999] e consentono il raggiungimento di una microzonaione di H livello.