NEXT GENERATION OF ITALIAN SHAKEMAPS

Licia FAENZA¹, Giovanni LANZANO², Rodolfo PUGLIA³, Valentino LAUCIANI⁴, Lucia LUZI⁵ and Alberto MICHELINI⁶

ABSTRACT

INGV has been producing shakemaps for Italy using the USGS-ShakeMap software since 2006. To respond to the recent technological developments and research outcomes (i.e., more data, better calibrated ground motion prediction equations and improved site classifications), it has become necessary the incorporation of these new elements into the routine shakemap generation. This will improve the quality and overall accuracy of the resulting maps. A second type of improvement follows from the progressive update of the maps generated just from automatic, real-time data processing and those obtained from reviewed, quality checked data of the Engineering Strong Motion database (ESM).

The ShakeMap configuration has been updated to the most accurate ground motion prediction equations after ranking of available models with the most recent Italian strong-motion data set. In particular, the GMPEs by Bindi et al (2011) will be used for active shallow crustal regions and volcanic areas (depth > 5km), Bindi et al. (2014) for events with focal depths > 35 km, occurring mainly in Northern Apennines, Skarlatoudis et al (2013) for the subduction zone (inlab) in the southern Tyrrhenian sea and Tusa and Langer (2016) for shallow volcanic areas (depth < 5km).

In order to account for site effects we used the Italian geological map at 1:100,000 scale (ISPRA, http://www.isprambiente.gov.it/it/ispra) reclassified into three EC8 categories. A comparison between the old and the new configurations has been carried out for the M5.9, October 26th, 2016, Visso earthquake (Central Apennines) showing an overall general improvement in the maps accuracy.

Keywords: shakemaps; peak parameters; GMPE

1. INTRODUCTION

ShakeMap is a software package (Wald et al. 1999; Worden et al. 2010, Worden and Wald, 2016) that generates maps of ground shaking for various peak ground motion (PGM) parameters, including the peak ground acceleration (PGA), peak ground velocity (PGV), and spectral acceleration response (PSA) at 0.3 s, 1.0 s and 3.0 s, and, in principle, for any other instrumentally derived intensities.

The main purpose for the implementation of the ShakeMap code at the Istituto Nazionale di Geofisica e Vulcanologia (INGV, National Institute of Geophysics and Vulcanology) is that of supporting the Dipartimento della Protezione Civile (DPC, Civil Protection Department) by providing a first order assessment of the experienced ground shaking (Michelini et al., 2008). Shakemaps are determined for all earthquakes with M≥3.0. At its core, ShakeMap is a seismological-based, interpolation algorithm that exploits the available observed ground motions and the available seismological knowledge to produce maps of ground motion at local and regional scales. Thus, in addition to observations, the fundamental ingredients for obtaining shakemaps are the ground-motion prediction equations (GMPEs; i.e., empirical equations to estimate the ground motion as a function of earthquake

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magnitude and style of faulting, source-to-site distance and the site conditions) and the $V_{S,30}$ values, to predict ground motion at soil sites using predefined amplification factors.

In this paper, we present the next generation of Italian shakemaps that rely on new or recent GMPEs, selected on the basis of a ranking procedure, and a new soil map, obtained by classifying the geologic units of the 1:100,000 scale geological map of Italy, available at ISPRA (http://www.isprambiente.gov.it/it/ispra).

2. RANKING OF GMPEs

In order to rank the ground motion predictive models, the Italian territory has been subdivided into three zones according to the prevailing tectonic regime (Figure 1) and earthquake depth.

1) Shallow Active Crustal Regions (SACRs) characterized by shallow (< 35 km) seismic events;
2) Volcanic Areas (VAs) (Mount Etna, Aeolian Islands, Ischia island, Phlegrean fields and Vesuvius, Stromboli);
3) Subduction Zones (SZs) corresponding to southern Tyrrhenian sea.

Figure 1 shows in map view the three zones, that partially overlap, and the events with magnitude larger than 3 and depth $\geq$ 35 km since 1985. Events with depth > 35 km and not associated to a subduction zone have been considered separately (hereinafter DE); according to the Italian seismic catalogue they mainly occur in the Northern Apennines.

A ranking procedure was applied to select the best performing GMPE for each zone and the deep events in Northern Apennines (DE). Eleven GMPEs, calibrated on different data sets (Italian, European, worldwide), were tested for SACR. Since some of these GMPEs use different source-to-site distance metrics, the resulting combination gives 14 models (Table 1).

Table 1. List of the candidate GMPEs for the application to SACRs (Style of faulting: N = normal, R = reverse, SS = strike-slip, U= unknown, HW= hanging wall effects).

<table>
<thead>
<tr>
<th>Name</th>
<th>Code</th>
<th>Area</th>
<th>M range</th>
<th>R range (km)</th>
<th>Site class</th>
<th>Style of faulting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrahamson et al (2014)</td>
<td>ASK14</td>
<td>Worldwide</td>
<td>3 - 7.9</td>
<td>0 - 300</td>
<td>$V_{S,30}$</td>
<td>N, R, SS, HW</td>
</tr>
<tr>
<td>Akkar and Bommer (2010)</td>
<td>AB10</td>
<td>Europe</td>
<td>5 - 7.6</td>
<td>0 - 100</td>
<td>3 classes</td>
<td>N, R, SS</td>
</tr>
<tr>
<td>Akkar et al (2014)</td>
<td>ASB14</td>
<td>Europe</td>
<td>4.7 - 7.6</td>
<td>0 - 200</td>
<td>$V_{S,30}$</td>
<td>SS, R, N</td>
</tr>
<tr>
<td>Bindi et al (2011)</td>
<td>ITA10</td>
<td>Italy</td>
<td>4.1 - 6.9</td>
<td>0 - 200</td>
<td>EC8</td>
<td>N, R, SS, U</td>
</tr>
<tr>
<td>Bindi et al (2014)</td>
<td>BND14</td>
<td>Europe</td>
<td>4 - 7.6</td>
<td>0 - 300</td>
<td>4 Classes</td>
<td>N, R, SS, U</td>
</tr>
<tr>
<td>Boore et al (2014)</td>
<td>BSSA14</td>
<td>Worldwide</td>
<td>3 - 7.9</td>
<td>0 - 400</td>
<td>$V_{S,30}$</td>
<td>N, R, SS, U</td>
</tr>
<tr>
<td>Campbell &amp; Bozorgnia (2014)</td>
<td>CB14</td>
<td>Worldwide</td>
<td>3 - 7.9</td>
<td>0 - 300</td>
<td>$V_{S,30}$</td>
<td>N, R, SS, HW</td>
</tr>
<tr>
<td>Cauzzi et al (2015)</td>
<td>CZ15</td>
<td>Worldwide</td>
<td>4.5 - 7.9</td>
<td>0 - 150</td>
<td>$V_{S,30}$</td>
<td>SS, N, R</td>
</tr>
<tr>
<td>Chiou &amp; Youngs (2014)</td>
<td>CY14</td>
<td>Worldwide</td>
<td>3.1 - 7.9</td>
<td>0 - 400</td>
<td>$V_{S,30}$</td>
<td>N, R, SS, HW</td>
</tr>
<tr>
<td>Derras et al (2014)</td>
<td>DBC14</td>
<td>Europe</td>
<td>3.6 - 7.6</td>
<td>0 - 550</td>
<td>$V_{S,30}$</td>
<td>N, R, SS, U</td>
</tr>
<tr>
<td>Kuehn &amp; Scherbaum (2015)</td>
<td>KS15</td>
<td>Europe</td>
<td>4 - 7.6</td>
<td>0 - 200</td>
<td>$V_{S,30}$</td>
<td>SS, N, R</td>
</tr>
</tbody>
</table>

The selection includes a model calibrated for Italy (Bindi et al., 2011), the most recent models derived for Europe (derived from the RESORCE dataset), the NGA-West2 programme, the GMPE by Akkar and Bommer (2010), calibrated for Europe and currently implemented in ShakeMap in Italy (Michelini et al., 2008), and the global model by Cauzzi et al. (2015), calibrated on a data set different from that used for NGA-West2.

All the models are defined for geometric mean (GM) or for RotD50, orientation-independent median value of horizontal components, according to Boore (2010). As shakemaps are released for the
maximum of the horizontal components, we used the empirical relation by Beyer and Bommer (2006) to convert from one to the other.

Since no specific GMPEs are available for the southern Tyrrhenian sea, three existing GMPEs were selected. They were derived for the Hellenic arc (Skarlatoudis et al., 2013; HEL13) and worldwide subduction zones (Zhao et al., 2006 ZHA06; Abrahamson et al., 2015 HYDR15). The candidate models for volcanic areas are the ones proposed by Tusa and Langer (2016) (TL16), calibrated for the Mount Etna area, and by Faccioli et al. (2010) (FAC10), which has been used in the European seismic hazard map for volcanic areas (SHARE project, Woessner et al. 2015).

The candidate models for events with depth > 35 km, not associated to a subduction zone, are selected among the SACRs models (Table 1) expressed in terms of hypocentral or rupture plane distances. In this case we could test 6 out of the 11 models of Table 1.

![Figure 1. Zonation of the Italian territory for the shakemap calculation.](image)

### 2.1 Data sets

We prepared strong-motion datasets to test GMPEs by selecting events and associated parametric data extracted from the waveforms from the Engineering Strong-Motion database (http://esm.mi.ingv.it, Luzi et al. 2016). Records were processed according to the procedure by Puglia et al. (2018).

The data set for SACRs includes:

- Events with focal depth ≤ 35 km and magnitude ≥ 3.5.
- Events with style of faulting and with Mw determined by moment tensor inversion (RCMT, Pondrelli et al. 2011; TDMT, Scognamiglio et al., 2009; Krieger et al. 2012).
- Exclusion of analog records and low sampled events used to derive Bindi et al. (2011).

As events with Mw > 6.5 in Italy are represented only by the 1980 Irpinia (Mw 6.9), we increased the data set with 6 well-sampled events occurred outside Italy (Japan, Turkey, Greece and Iran) with Mw up to 7.5 and known fault geometry.

The data set for SZs includes:

- Waveform from both accelerometers and broadband instruments;
- Events with local magnitude larger than 4.0;
- Events with depth larger than 40 km in the southern Tyrrhenian and Ionian seas;

The data set for VAs includes:
- Waveform parameters from accelerometers and broadband instruments;
- Events with local magnitude larger than 3.5;
- Events in the Mount Etna and in the Aeolian Islands.

The data set for deep events outside subduction zones (DEs) includes:
- Events with local magnitude larger than 4.0;
- Events with depth larger than 35 km in the Northern Apennines and Central Sicily;
- Waveform parameters from accelerometers and broadband instruments.

Figure 2 shows the magnitude-distance distribution of the data sets for the ranking of GMPEs.
2.2 GMPE ranking

In order to evaluate the performance of each GMPE, we have used the LLH method by Scherbaum et al. (2009), which is considered as a standard procedure for the selection of predictive models (Delavaud et al. 2012). The method consists in determining the distance between the unknown model, representing the reality, and the candidate model, based on the concept of likelihood, which gives the probability of the observed data under a model.

The LLH scores of the candidates GMPEs are shown in Table 2 (SACRs) and Table 3 (SZs, VAs and DEs). The ranking is averaged over the 5 Intensity Measures of the shakemaps (PGA, PGV, 0.3, 1 and 3s).

Table 2. Final rank of GMPEs for Shallow Active Crustal Regions (SACRs). $R_{\text{JB}}$ = Joyner-Boore distance, $R_{\text{epi}}$ = epicentral distance, $R_{\text{hypo}}$ = hypocentral distance.

<table>
<thead>
<tr>
<th>#</th>
<th>GMPEs</th>
<th>Mean LLH</th>
<th>#</th>
<th>GMPEs</th>
<th>Mean LLH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ITA10</td>
<td>1.793</td>
<td>8</td>
<td>ASK14</td>
<td>1.923</td>
</tr>
<tr>
<td>2</td>
<td>ASB14 ($R_{\text{epi}}$)</td>
<td>1.803</td>
<td>9</td>
<td>CZ15</td>
<td>1.933</td>
</tr>
<tr>
<td>3</td>
<td>ASB14 ($R_{\text{hypo}}$)</td>
<td>1.829</td>
<td>10</td>
<td>CY14</td>
<td>1.950</td>
</tr>
<tr>
<td>4</td>
<td>ASB14 ($R_{\text{JB}}$)</td>
<td>1.838</td>
<td>11</td>
<td>CB14</td>
<td>2.056</td>
</tr>
<tr>
<td>5</td>
<td>BND14 ($R_{\text{JB}}$)</td>
<td>1.853</td>
<td>12</td>
<td>KS15</td>
<td>2.100</td>
</tr>
<tr>
<td>6</td>
<td>BND14 ($R_{\text{hypo}}$)</td>
<td>1.892</td>
<td>13</td>
<td>AB10</td>
<td>2.511</td>
</tr>
<tr>
<td>7</td>
<td>BSSA14</td>
<td>1.921</td>
<td>14</td>
<td>DBC14</td>
<td>2.629</td>
</tr>
</tbody>
</table>

Table 3. Final rank of GMPEs for Subduction Zones (SZs), Volcanic Areas (VAs) and Deep Events (DEs). $R_{\text{hypo}}$ is the hypocentral distance.

<table>
<thead>
<tr>
<th>#</th>
<th>GMPEs</th>
<th>Mean LLH</th>
<th>#</th>
<th>GMPEs</th>
<th>Mean LLH</th>
<th>#</th>
<th>GMPEs</th>
<th>Mean LLH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HYDR15</td>
<td>3.418</td>
<td>1</td>
<td>TL16</td>
<td>2.120</td>
<td>1</td>
<td>BND14 ($R_{\text{hypo}}$)</td>
<td>2.526</td>
</tr>
<tr>
<td>2</td>
<td>HEL13</td>
<td>3.696</td>
<td>2</td>
<td>FAC10</td>
<td>3.374</td>
<td>2</td>
<td>CY14</td>
<td>2.628</td>
</tr>
<tr>
<td>3</td>
<td>ZHA06</td>
<td>9.000</td>
<td>3</td>
<td>ASK14</td>
<td>2.680</td>
<td>3</td>
<td>CB14</td>
<td>2.742</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>ASB14 ($R_{\text{hypo}}$)</td>
<td>2.769</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6</td>
<td>CZ15</td>
<td>2.798</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results of the ranking procedure indicate that the most appropriate model for SACRs consists of the GMPE calibrated for Italian data by Bindi et al (2011); Tusa and Langer (2016) is selected for VA, while for earthquakes with depth $\geq 35$ km outside subduction zones (e.g. northern Apennines), the GMPE developed by Bindi et al. (2014) are adopted. The model for the Hellenic arc (Skarlatoudis et al, 2013) is preferred for subduction zones with respect to global model by Abrahamson et al. (2015), considering that they have similar performances but HEL13 is characterized by a simpler functional form, especially for site effects term. Finally, the four selected models account for the site effects through the EC8 soil categories (CEN, 2003).
2. SOIL MAP

The USGS ShakeMap procedure predicts ground motion at unknown sites (i.e., no observed ground motion values) including site effects. As the four selected predictive models work for EC8 soil categories, the geologic map at 1:100,000 scale of Italy (http://www.isprambiente.gov.it/it/ispra) has been classified according to surface geology according to Di Capua et al (2011). Considering the accuracy of the geological map, we could determine only classes EC8- A, B and C, that can be considered a proxy of rock, stiff and soft soils. The Class D in the original map by Di Capua et al (2011) was merged with class C. Figure 3 shows the result of the categorization.

Class A sites are prevalently igneous, metamorphic and limestone rocks in the Alps, limestone in the Apennines and Sicily and igneous rocks in Sardinia. Class B is the most widespread soil type, by definition, and includes soft rocks such as marly limestones, sandstones and marly sandstones and volcanic tuff. Class C has been attributed to alluvial deposits, such as the Po plain, in Northern Italy, smaller plains in central Italy (e.g. Arno and Tiber river valleys or “Piana Campana”) and close shaped inter-mountain basins (e.g. Norcia, Fucino).

Figure 3. Soil map of Italy built from the geological map of Italy (http://www.isprambiente.gov.it/it/ispra) with the EC8 A-C classes mapped according to the different outcropping rock-types.

3. SHAKEMAP IMPLEMENTATION

The ShakeMap procedure has been implemented for Italy at INGV since 2006 (http://shakemap.rm.ingv.it) and it is fully described in Michelini et al. (2008). The data used to
generate the shakemaps are recorded in real-time by the National Seismic Network (e.g., Michelini et al., 2016) and offline by the “Rete Accelerometrica Nazionale” (http://ran.protezionecivile.it/IT/index.php). Manually reviewed data from the ESM database (Luzi et al., 2016) are used to update the maps as they become available. The new generation of shakemaps results from the implementation of the new GMPEs and new site amplification correction described in the previous sections. The main differences between old and new implementation of ShakeMap are summarised in Table 4.

Table 4. Summary of main differences between old and new Shakemaps configurations.

<table>
<thead>
<tr>
<th>Shakemap setting</th>
<th>Old implementation (Michelini et al., 2008)</th>
<th>New implementation (this work)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcanic areas</td>
<td>Not accounted for</td>
<td>Etna volcano, Aeolian islands, Vesuvius, Phlegraean Field, Ischia.</td>
</tr>
<tr>
<td>Deep events</td>
<td>Not accounted for</td>
<td>Calabrian arc subduction (depth ≥ 40 km) and Northern Apennines (depth ≥ 35 km)</td>
</tr>
<tr>
<td>Different GMPEs</td>
<td>Akkar and Bommer, 2010, for M≥5.5; Malagnini et al. (2000, 2002) and Morasca et al. (2006) otherwise</td>
<td>All GMPEs applied to magnitude &gt;=3.5</td>
</tr>
<tr>
<td>according to magnitude</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site amplification</td>
<td>$V_{s30}$ extrapolated from geologic map and amplification values modified from Borcherdt (1994)</td>
<td>EC8 A-C classes from 1:100,000 scale geologic map. Site coefficients from GMPEs</td>
</tr>
<tr>
<td>corrections</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. COMPARISON BETWEEN NEW AND OLD IMPLEMENTATION

In order to assess the improvement resulting from the new configuration, we present the shakemaps that have been determined for the October 26th, 2016, M5.9 Visso earthquake in Central Italy. There are two types of comparisons that we have performed. The first consists in verifying the differences when all the available observations are used for both old and new configurations. This comparison evidences areas where differences are due to the different GMPEs and site corrections. Where the station coverage is dense, no significant differences are expected because the data will have a dominant effect. The second test aims to demonstrate the robustness of the old and new shakemap configuration in case of a poor data coverage, as we believe that, when appropriate modeling of ground motion attenuation and site effects corrections are used, small differences are expected between shakemaps obtained with a complete or a reduced data coverage. The results of the first test are shown in Figure 4. The maps indicate small differences between the two configurations in areas far away from the seismic source, while the main differences occur close to the epicentre. In particular, the new shakemap configuration results in overall larger values. This “overshooting” of the new configuration results from the exclusion of observed values recognised as “outliers” by the ShakeMap software (i.e., the software excludes observations that are outside 3-sigma of the adopted GMPE). In the old configuration 6 stations were excluded (as they exceed 3-sigma of the Akkar and Bommer, 2010), while all the observations are kept in the new one. Moreover, differences arise from the adoption of an alternative scheme for the inclusion of site effects. This all
evidences that the new configuration implemented in this work is less likely to exclude recorded ground motions thus suggesting being more realistic.

Figure 4. Comparison between the two configurations using the complete data set. Top row: old configuration; middle row: new configuration; Bottom row: differences between the two ShakeMap configurations. Solid triangles in the bottom row, indicate the stations excluded as outliers in the old configuration. The orange box indicates the area selected for the second test.

The results of the second comparison are shown in Figure 5. To this purpose, we have identified an area that is well covered by stations (see box in Figure 4) and we have calculated the shakemaps (old and new configuration) with this reduced data set. The region in Figure 4 was selected because of the dense data coverage and because it should be somewhat unaffected by the finite source complexities, given the distance from the source and its small area. We expect that the more robust shakemap
configuration will be that with the smaller differences between whole and the depleted data set. The results are shown in Figure 5 and summarized in Table 5 using some simple statistics. Table 5 in particular, shows that, although the differences are very small overall, the new configuration is more robust, as the differences in the shakemaps, obtained with the complete versus the reduced data set, are smaller.

![Figure 5. Maps of the differences between the shakemaps calculated with the complete and the reduced data set (solid, black triangles indicate the removed stations). Top row: differences with the new configuration; Bottom row: differences with the old configuration. Left column: PGA; Right column: PGV. Differences have been calculated at individual pixels in the target area shown in Figure 4.](image)

Table 5. Mean and standard deviation of the differences in the target area of the new and old ShakeMap configuration (see text). The reported statistics are determined from the grid point values within the target area of Figure 4. In bold the smallest values.

<table>
<thead>
<tr>
<th>PGM</th>
<th>Mean (old)</th>
<th>Std. Dev (old)</th>
<th>Mean (new)</th>
<th>Std. Dev (new)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PGA</td>
<td>-0.050</td>
<td>0.524</td>
<td><strong>0.017</strong></td>
<td>0.487</td>
</tr>
<tr>
<td>PGV</td>
<td>-0.101</td>
<td>0.474</td>
<td><strong>-0.033</strong></td>
<td>0.376</td>
</tr>
<tr>
<td>PSA03</td>
<td><strong>0.115</strong></td>
<td>1.188</td>
<td>0.311</td>
<td><strong>1.099</strong></td>
</tr>
<tr>
<td>PSA10</td>
<td>-0.157</td>
<td>0.360</td>
<td><strong>-0.064</strong></td>
<td>0.335</td>
</tr>
<tr>
<td>PSA30</td>
<td>-0.019</td>
<td>0.050</td>
<td><strong>0.004</strong></td>
<td>0.048</td>
</tr>
</tbody>
</table>
5. CONCLUSIONS

In this paper, we have presented the implementation of the new configuration of the software ShakeMap for Italy. This new configuration is motivated by the improved knowledge gained since 2006 (i.e., when the first implementation was configured) on the attenuation relations (GMPEs) and the site effects (Michelini et al., 2008). The new configuration replaces the outdated GMPEs regionalization dependent on earthquake magnitude (threshold M = 5.5) and the V<sub>s</sub> 30 regionalization extrapolated from the geologic map combined with the modified Borcherdt (1994) for site amplification.

The selection of the most appropriate GMPEs is carried out by adopting the LLH statistical ranking (Scherbaum et al., 2009).

The following GMPEs have been selected:
- Bindi et al. (2011) for shallow active crustal regions (<35 km);
- Tusa and Langer (2016) for volcanic areas;
- Bindi et al (2014) for events deeper than 35 km outside the subduction zone.
- Skarlatoudis et al. (2016) for the Calabrian arc subduction zone.

Differently from the initial shakemap configuration, we use the site effect correction as the GMPEs coefficients (EC8 soil categories). To evaluate the site amplifications, a new soil map was derived from the Italian geological map at 1:100,000 scale (ISPRA, http://www.isprambiente.gov.it/it/ispra), reclassified by Di Capua et al (2011).

The new configuration was tested for one earthquake of the 2016 Central Italy sequence. In general, we found negligible differences between the two configurations in areas far away from the seismic source, while the main differences occur in the epicentral area. In particular, we found that the new shakemap configuration reduces conspicuously the number of data “outliers” when compared to those resulting from the old configuration. This observation alone supports that the new configuration is closer to the unknown real one. Moreover, our second test shows that the shakemaps resulting from the new configuration are more robust since, as observations are removed, the resulting map features smaller differences when compared to those obtained from the interpolation of the complete set of observations. These tests, although quite promising, cannot be considered yet exhaustive since additional analyses are required on a larger number of events in other areas in Italy.

6. REFERENCES


