# Testing regression models for estimating Newmark co-seismic displacements in moderate to low seismic areas


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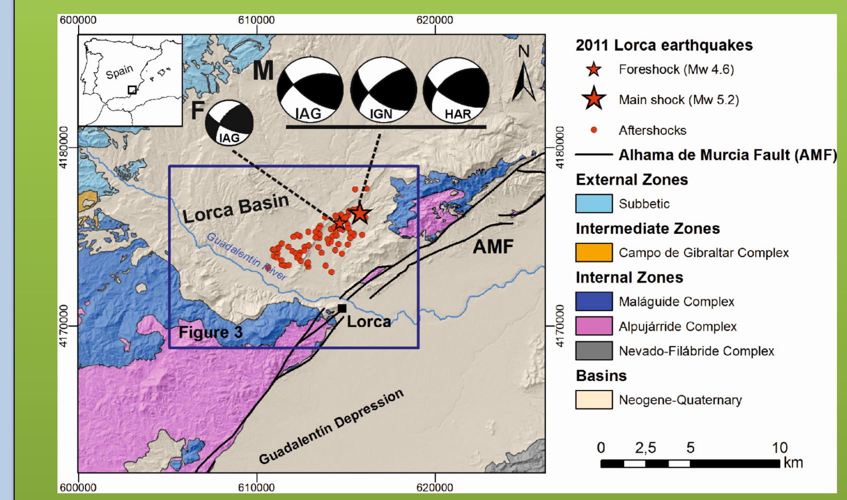
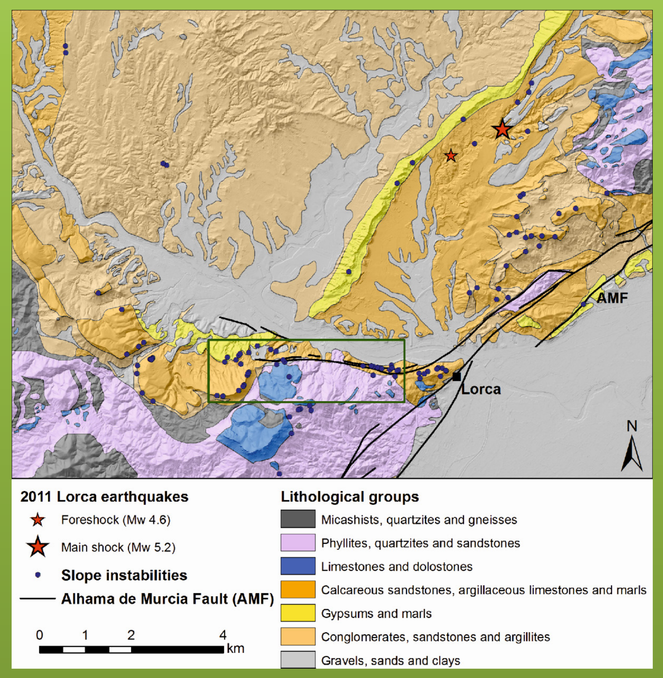
## INTRODUCTION

The assessment of earthquake-triggered landslide hazard at a regional scale always implies important simplifications. Uncertainties in accurately defining strong ground-motion characteristics at a particular site, as well as in modeling the geotechnical parameters of the slope mass and its dynamic behavior, make earthquake-triggered landslide assessment a very complex matter. The most common procedures followed in regional assessments deal with the well-known Newmark sliding rigid-block method.
The estimation of Newmark displacements in regional hazard assessment is usually done by making use of regression models based on basic earthquake parameters (magnitude and distance) and/or simple strong ground-motion parameters (i.e. PGA, Arias intensity). At present, different authors have proposed regression models from earthquakes occurred around the world, usually of moderate to high magnitude ($M_w$ > 6.0).

In this work, we compare a number of these regression equations to select one that could be used to study areas with moderate to low magnitude earthquakes. This type of seismic scenario is the most common in Spain, where during the last decades several moderate to low magnitude earthquakes ($M_w$ < 5.5) have triggered multiple slope instabilities. In particular, the 2011 Lorca earthquake ($M_w$ = 5.2) triggered far more slope instabilities than any other instrumental earthquake recorded in Spain. We have used the well know data of this seismic event (magnitude, distances, slope instabilities location, geotechnical parameters) to estimate Newmark displacements on the earthquake-triggered landslides location to select the regression equation which offer the best results. This regression equation could be used in similar areas with moderate to low magnitude earthquakes for regional hazard assessments.

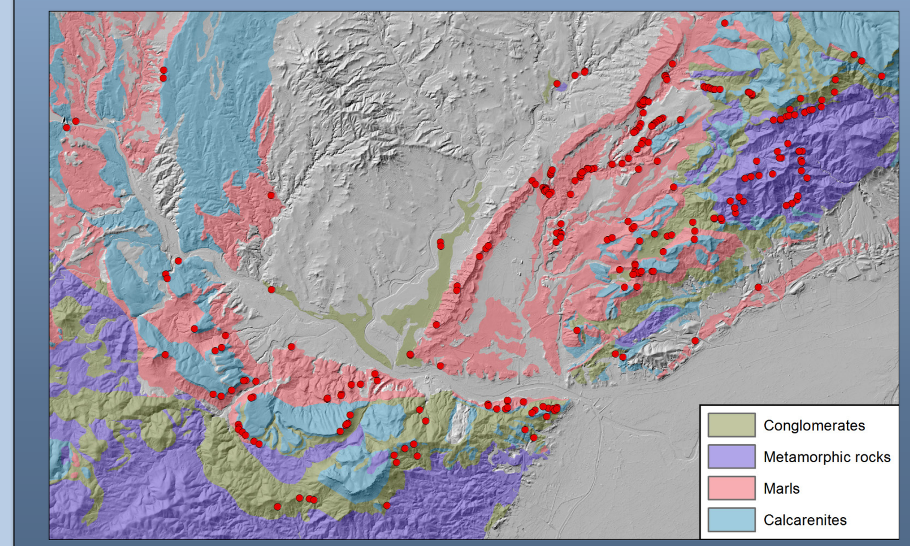



Epicentres of the 2011 Lorca seismic series (IGN, 2011). Only magnitude ≥ 1.0 events are plotted. The main shock ($M_w$=5.2) and the strongest precursor ($M_w$=4.6) are represented by red stars. The focal mechanisms of the largest foreshock (F) and the main shock (M) as calculated by several agencies are also shown: IAG: Instituto Andaluz de Geofísica, IGN: Instituto Geográfico Nacional, HAR: Harvard CMT.

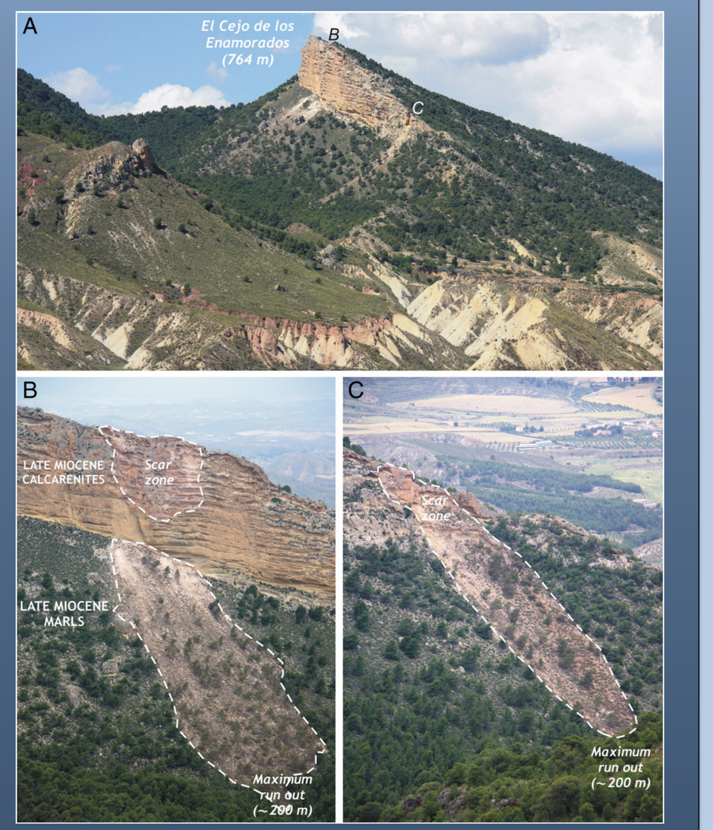



Distribution of the main slope instabilities triggered by the 2011 Lorca earthquakes (Rodríguez Peces *et al.*, 2014).

## CO-SEISMIC LANDSLIDES DURING 2011 LORCA EARTHQUAKE

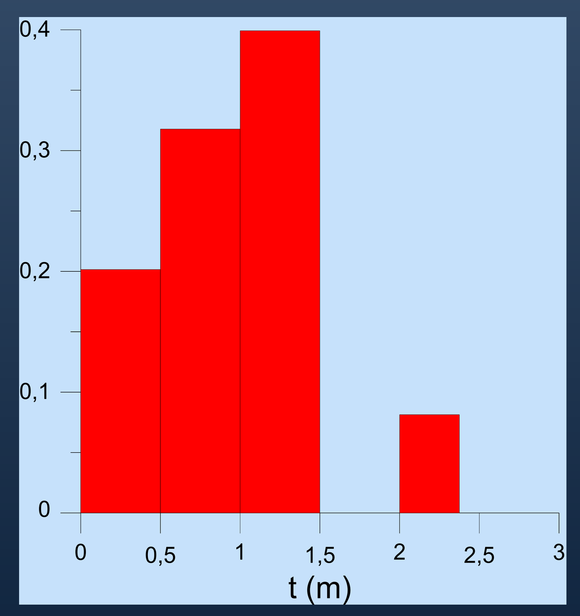



Typical disrupted-type slope instabilities triggered by 2011 Lorca earthquakes (Rodríguez Peces *et al.*, 2014). A) One of the largest rock falls inventoried (~100 $m^3$); B) Example of damage in buildings related to the earthquake-triggered rock falls.



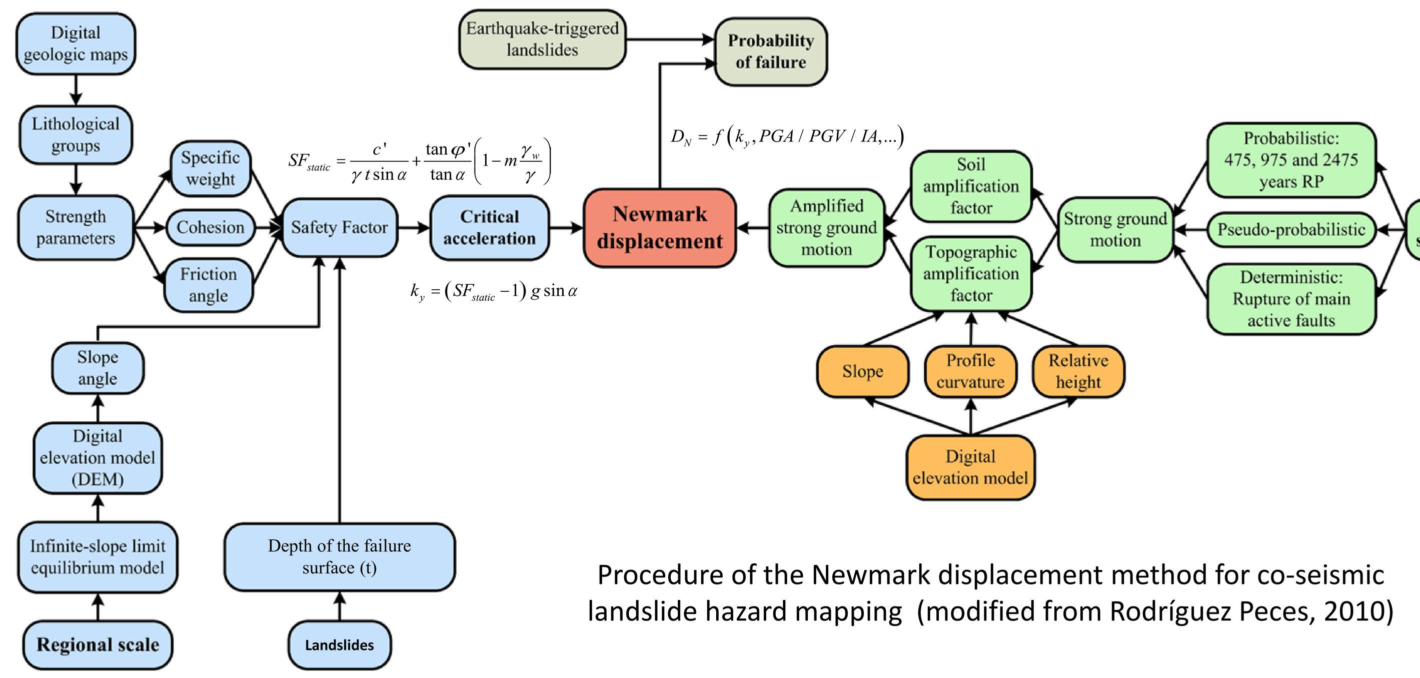

Examples of seismically-induced landslides at the ridge of the Cejo de los Enamorados during the 2011 Lorca earthquake (Alfaro *et al.*, 2012).

### Depth of the failure surface (t)




| | |
|---|---|
| t = 0 - 0.5 m | 20.2 % |
| t = 0.5 - 1 m | 31.8 % |
| t = 1 - 2 m | 39.9 % |
| t > 3 m | 8.1 % |

## METHODOLOGY




Procedure of the Newmark displacement method for co-seismic landslide hazard mapping (modified from Rodríguez Peces, 2010)

### Newmark displacement regression models

**Based on critical acceleration ratio ($a_c$/PGA) - Jibson (2007)**

$$\log D_N = 0.215 + \log\left[\left(1-\frac{a_c}{a_{max}}\right)^{2.341}\left(\frac{a_c}{a_{max}}\right)^{-1.438}\right] \pm 0.510$$

**Based on critical acceleration ratio ($a_c$/PGA) and Magnitude (M) - Jibson (2007)**

$$\log D_N = -2.710 + \log\left[\left(1-\frac{a_c}{a_{max}}\right)^{2.335}\left(\frac{a_c}{a_{max}}\right)^{-1.478}\right] + 0.424\mathbf{M} \pm 0.454,$$

**Based on Arias Intensity ($I_A$) and critical acceleration ($a_c$) - Jibson (2007)**

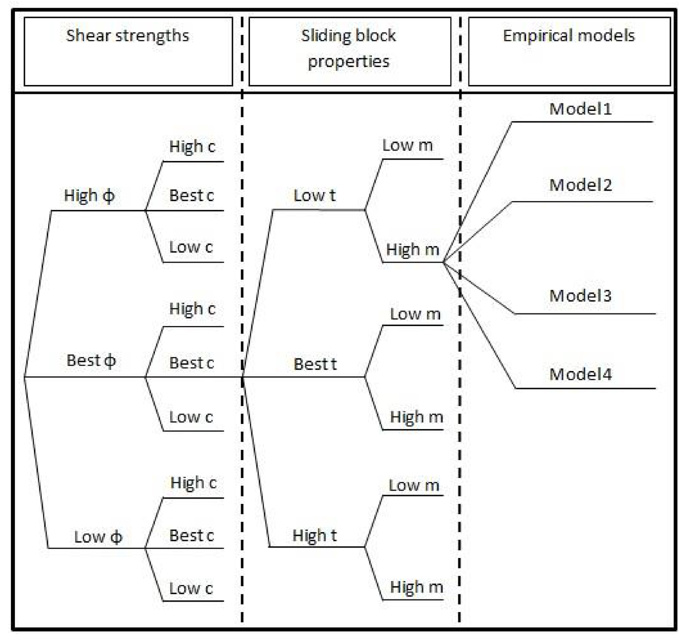
$$\log D_N = 2.401\log I_a - 3.481\log a_c - 3.230 \pm 0.656$$

**Based on critical acceleration ratio ($a_c$/PGA) and Magnitude (M) - Rathje and Saygili (2009)**

$$\ln D = a_1 + a_2\left(\frac{k_y}{PGA}\right) + a_3\left(\frac{k_y}{PGA}\right)^2 + a_4\left(\frac{k_y}{PGA}\right)^3 + a_5\left(\frac{k_y}{PGA}\right)^4 + a_6\ln(PGA) + a_7(M-6)$$

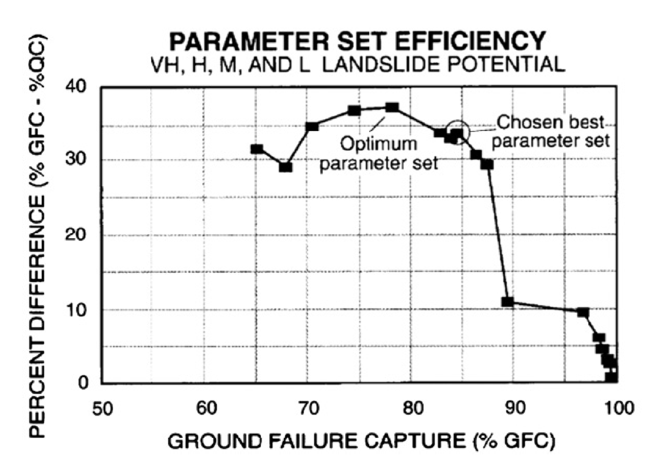
| Parameter | Scalar Model (PGA, M) |
|---|---|
| $a_1$ | 4.89 |
| $a_2$ | -4.85 |
| $a_3$ | -19.64 |
| $a_4$ | 42.49 |
| $a_5$ | -29.06 |
| $a_6$ | 0.72 |
| $a_7$ | 0.89 |

### Uncertainty reduction




Example of logic tree for probabilistic seismic landslide hazard mapping (Wang and Rathje, 2015).

### Selection of best model




Example of selection of the best parameter set for seismic landslide hazard mapping (McCrink, 2001).

## STRENGTH PARAMETERS

**Rocks**

| | | Calcarenites | | Conglomerates | | Metamorphic rocks | |
|---|---|---|---|---|---|---|---|
| | | c (kPa) | Φ (°) | c (kPa) | Φ (°) | c (kPa) | Φ (°) |
| t = 0.5 m | Low | 0.34 | 43 | 0.87 | 53 | 0.37 | 42 |
| | Best | 0.40 | 46 | 3.34 | 60 | 0.58 | 49 |
| | High | 0.44 | 48 | 5.22 | 62 | 1.53 | 57 |
| t = 1 m | Low | 0.61 | 41 | 1.45 | 51 | 0.65 | 41 |
| | Best | 0.71 | 45 | 4.59 | 57 | 1.01 | 47 |
| | High | 0.77 | 47 | 6.78 | 60 | 2.38 | 55 |
| t = 2 m | Low | 1.08 | 40 | 2.45 | 49 | 1.16 | 40 |
| | Best | 1.25 | 43 | 6.58 | 55 | 1.74 | 46 |
| | High | 1.36 | 45 | 9.21 | 58 | 3.80 | 53 |
| t = 3 m | Low | 1.51 | 39 | 3.33 | 47 | 1.62 | 39 |
| | Best | 1.74 | 42 | 8.29 | 54 | 2.41 | 45 |
| | High | 1.90 | 44 | 11.25 | 56 | 5.05 | 52 |

Values obtained from geomechanical stations assuming a Barton-Bandis failure criterion.

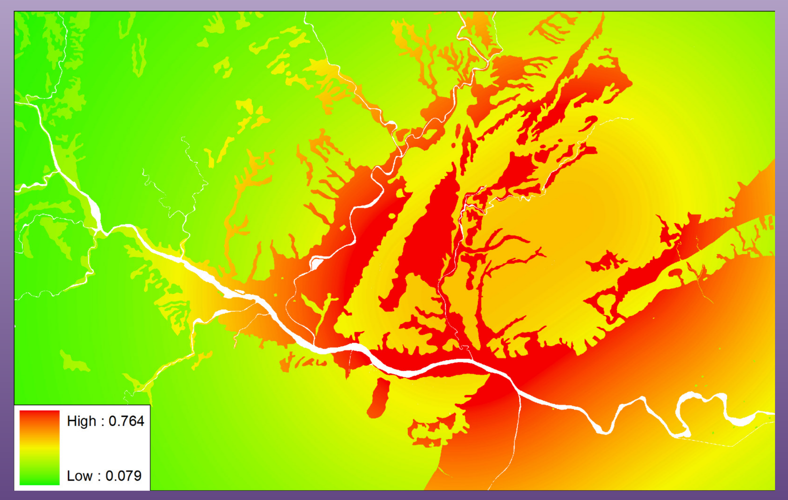
**Soils**

| | Marls | |
|---|---|---|
| | c (kPa) | Φ (°) |
| Low | 3.91 | 19 |
| Best | 28.05 | 26 |
| High | 127.00 | 37 |

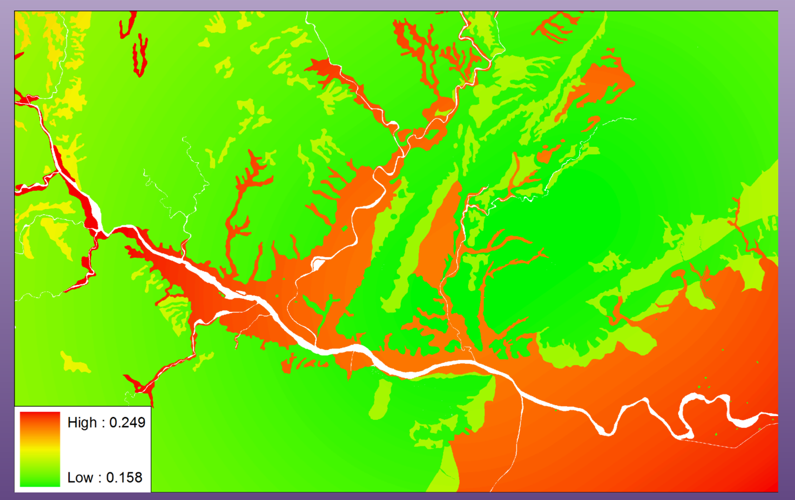
Values obtained from direct shear tests assuming a Mohr-Coulomb failure criterion.

## DETERMINISTIC SEISMIC SCENARIOS FOR 2011 LORCA EARTHQUAKE

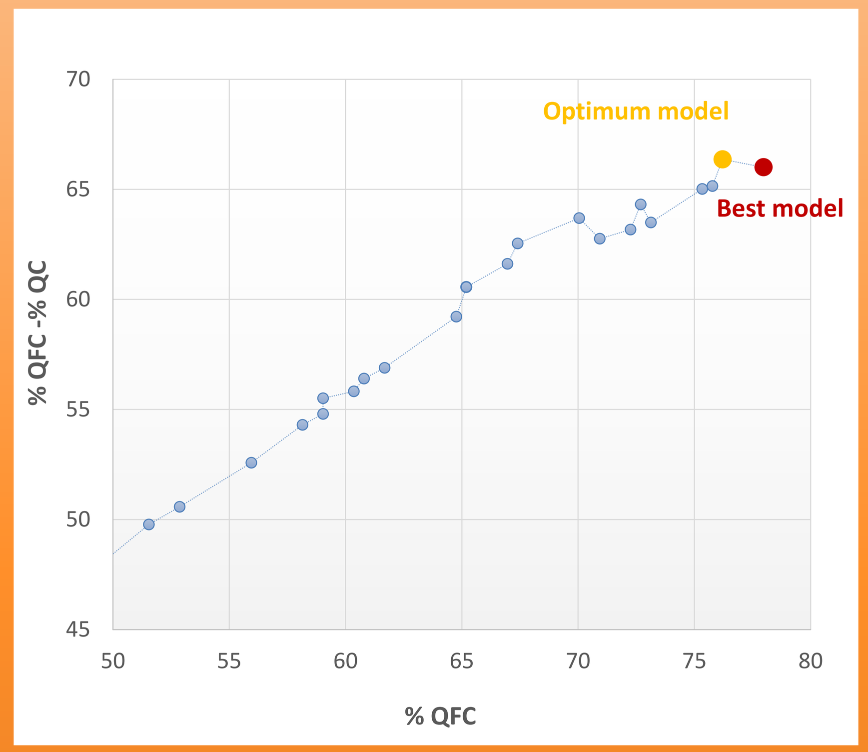
Arias Intensity (IA, m/s)



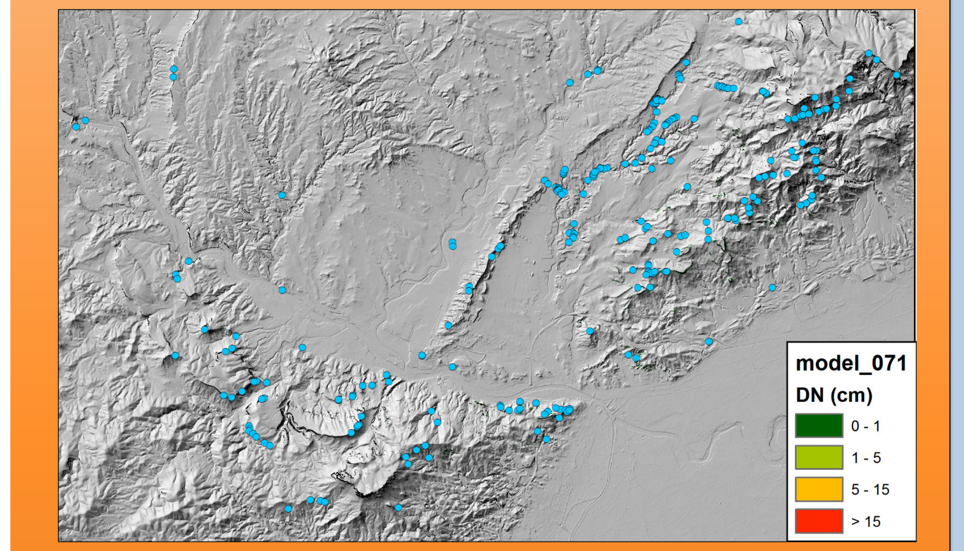

Peak Ground Acceleration (PGA, g units)



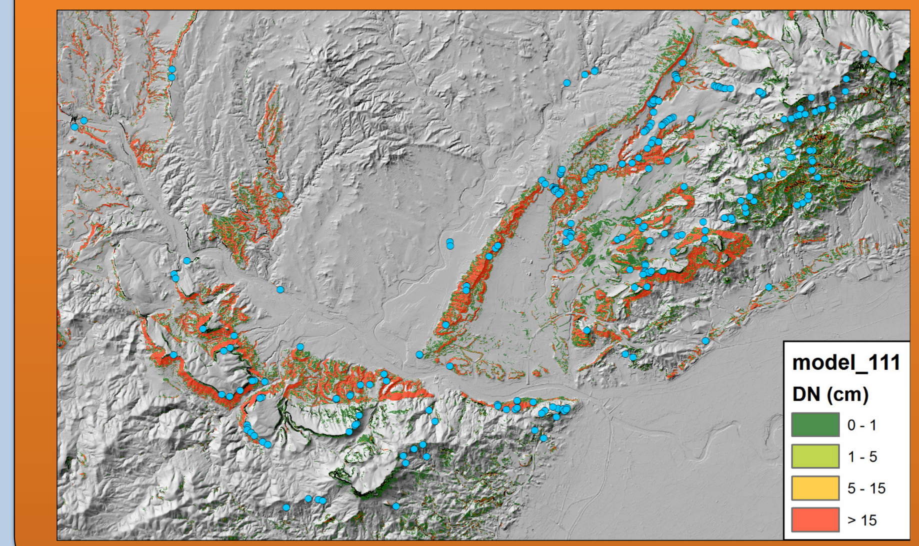

## SEISMIC LANDSLIDE HAZARD MAPS FOR 2011 LORCA EARTHQUAKE



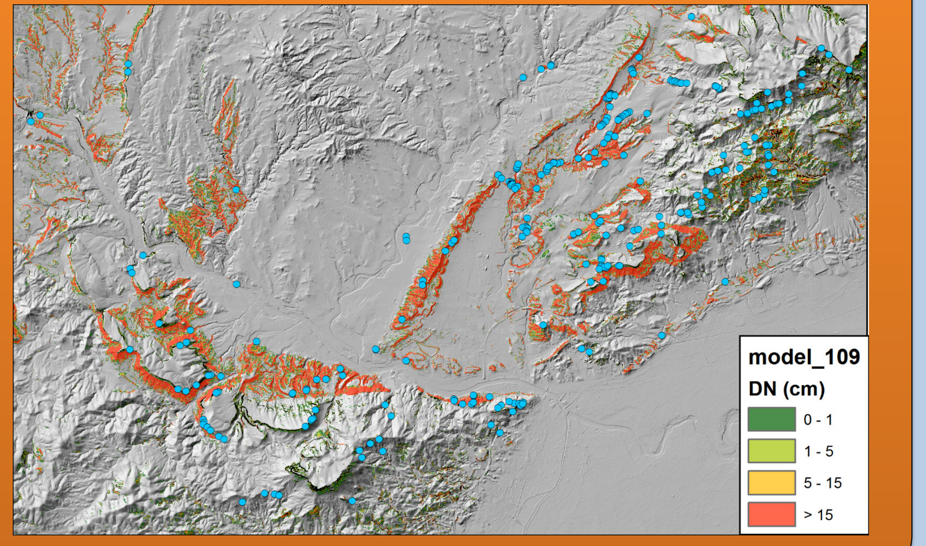

Worst model




Optimum model




Best model




## CONCLUSIONS

We compare a number of Newmark displacements regression equations to select one that could be used to seismic landslide hazard mapping in areas with moderate to low magnitude earthquakes.

The regression equation which offer the **optimum** results on the earthquake-triggered landslides location is the one that estimate Newmark displacement as a function of Arias intensity and critical acceleration (Jibson, 2007).

The regression equation which offer the **best** results on the earthquake-triggered landslides location is the one that estimate Newmark displacement as a function of critical acceleration ratio (Jibson, 2007). This regression equation could be used in similar areas with moderate to low magnitude earthquakes for regional hazard assessments.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