Supplement of

Simple rules to minimise exposure to coseismic landslide hazard

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Supplementary Information 1: Hazard area performance with optimised, global and hold-back parameters

At each of the six study sites we optimise the two parameters in the SHALRUN-EQ model required to predict hazard area, initiation angle ($\theta_m$) and stopping angle ($\theta_s$), by sampling values for each parameter uniformly in 1 degree increments over the range [20,70] for initiation angle and [0,50] for stopping angle, and imposing the requirement: $\theta_m > \theta_s$. For our objective function, we use the area under the receiver operating characteristic (ROC) curve, comparing landslide hazard derived from hazard area to the inventory of observed landslides at each site. The optimisation surfaces are shown in Figure S1. To generalise our results, we then take arithmetic means of the optimum initiation and stopping angles, to generate hazard area predictions using a single ‘global’ rule averaged over all six inventories (Table S1). To remove the influence of test data on the test itself, we re-run the hazard area prediction for each inventory as a hold back-test, in which we re-calculate the initiation and stopping parameters excluding the optimised values from that inventory and using only the remaining five inventories.

We find that the differences in ROC curves (Figure S2) and area under the curve values (Table S1) are fairly subtle. Hazard area with global average parameters performs well overall, with AUC values that range from 0.78 to 0.86. Hazard area with parameters that are optimised for each inventory offers only a slight further improvement, with AUC increased by <3% in each case (Table S1). Optimised initiation and stopping angles can differ quite radically between sites, ranging from 31-45˚ for initiation angle and from 3-19˚ for stopping angle. This might signal cause for concern about how feasible it is to find a single general rule, given such variability in optimum parameters between sites. However, hazard area skill is relatively insensitive to parameter variation close to the optimum parameters, as indicated by the relatively smooth and gentle peaks of the optimisation surfaces in Figure S1. Thus, the (sometimes large) differences between global and optimised parameter values do not translate into large performance differences between hazard area predictions using global or optimised parameters. The use of hold-back rather than global parameters results in an even smaller difference in performance; AUC values are reduced by <1% for every inventory and hazard area is still the best metric at all sites. For this reason, we include hold-back tests here but report results from global average parameters rather than hold-back parameters in the paper for simplicity. It is...
these global average parameters (initiation angle of 40° and stopping angle of 10° when rounded to one significant figure) that form the basis of our simple rule, and that we would recommend when applying the SHALRUN-EQ approach to a new location (in the absence of a landslide inventory with which to test and calibrate the parameters).

Table S1: Parameter values and areas under the ROC curve for the six inventories

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Area Under ROC Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hazard area</td>
</tr>
<tr>
<td></td>
<td>optimised</td>
</tr>
<tr>
<td>Initiation slope $\theta_i$ (°)</td>
<td>Stopping slope $\theta_s$ (°)</td>
</tr>
<tr>
<td>Finisterre</td>
<td>34</td>
</tr>
<tr>
<td>Northridge</td>
<td>41</td>
</tr>
<tr>
<td>Chichi</td>
<td>44</td>
</tr>
<tr>
<td>Wenchuan</td>
<td>39</td>
</tr>
<tr>
<td>Haiti</td>
<td>31</td>
</tr>
<tr>
<td>Gorkha</td>
<td>45</td>
</tr>
<tr>
<td>Average</td>
<td>39</td>
</tr>
<tr>
<td>$1\sigma$</td>
<td>6</td>
</tr>
</tbody>
</table>
Figure S1: Model predictive skill for SHALRUN-EQ for each of the six landslide inventories across reasonable ranges for the two parameters, initiation angle ($\theta_i$) and stopping angle ($\theta_s$). Predictive skill is quantified using area under the receiver operating characteristic curve. The six inventories are: a) Finisterre, b) Northridge, c) Chi-Chi, d) Wenchuan, e) Haiti, f) Gorkha. Symbols show the parameter combinations from site specific optimisation, global average, and hold-back average.
Figure S2: Receiver operating characteristic (ROC) curves for the six landslide inventories and five metrics examined here, as shown in Figure 6 of the paper, but with the addition of ROC curves for hazard area with (1) site-specific optimised parameters and (2) hold-back parameters (i.e., global averages from five sites excluding the test site). The six inventories are: a) Finisterre, b) Northridge, c) Chi-Chi, d) Wenchuan, e) Haiti, f) Gorkha. False positive rate is given by the number of false positives divided by the sum of false positives and true negatives. True positive rate is given by the number of true positives divided by the sum of true positives and false negatives. The 1:1 line represents the naïve (random) case. Curves plotting closer to the top left corner of each panel represent better model performance.
<table>
<thead>
<tr>
<th>Study site</th>
<th>Northridge</th>
<th>Finisterre</th>
<th>Chi-Chi</th>
<th>Wenchuan</th>
<th>Haiti</th>
<th>Gorkha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geology</td>
<td>Weakly cemented sedimentary rocks(^1)</td>
<td>Volcaniclastic &amp; volcanic rocks thrust over coarse-grained foreland deposits capped by limestones (^9)</td>
<td>Neogene sediments and older metasedimentary rocks (^{10})</td>
<td>Granitic massifs, a passive margin sequence, and a thick foreland basin succession (^{12})</td>
<td>Sub-parallel belts of igneous, metamorphic and sedimentary rocks (^{26})</td>
<td>Variably metamorphosed sedimentary and igneous rocks, some sedimentary metasedimentary (^{13})</td>
</tr>
<tr>
<td>Denudation rates</td>
<td>0.1-1 mm/yr(^{2})</td>
<td>up to 0.3 mm/yr (^{10})</td>
<td>3-7 mm/yr (^{14})</td>
<td>0.5 mm/yr (^{23})</td>
<td>(&lt;0.5) mm/yr (^{23})</td>
<td>0.3-3 mm/yr (^{14})</td>
</tr>
<tr>
<td>Koppen climate classification</td>
<td>Warm-summer Mediterranean (^{13})</td>
<td>Tropical (^{3})</td>
<td>Humid subtropical (^{3})</td>
<td>Humid subtropical (^{11})</td>
<td>Tropical (^{3})</td>
<td>Humid subtropical (^{3})</td>
</tr>
<tr>
<td>Temperature</td>
<td>1-18 °C (^{4})</td>
<td>26-27 °C (^{11})</td>
<td>22 °C (^{17})</td>
<td>15-17 °C (^{24})</td>
<td>25°C (^{29})</td>
<td>-6-18 °C (^{35})</td>
</tr>
<tr>
<td>Annual precipitation</td>
<td>0.3-0.9 m (^{8})</td>
<td>2.5 - 4 m (^{11})</td>
<td>2.5 m (^{11})</td>
<td>0.6 - 1.1 m (^{24})</td>
<td>~1.2 m (^{26})</td>
<td>0.5 - 3 m (^{32})</td>
</tr>
<tr>
<td>Vegetation</td>
<td>annual grassland, sage scrub, and chaparral with some piñon-juniper, oak and pine woodlands. (^{6})</td>
<td>tropical wet or tropical montane evergreen forest some sub-alpine grasslands. (^{12})</td>
<td>Subtropical moist broadleaf forests (^{18})</td>
<td>montane broad-leaved and conifer forest with some alpine shrub and steppe (^{29})</td>
<td>moist broadleaf forest some pine or dry broadleaf forest, with some savannah (^{10,30})</td>
<td>temperate broadleaf and coniferous forests with some alpine tundra (^{36})</td>
</tr>
<tr>
<td>Earthquake magnitude</td>
<td>(M_w 6.7)</td>
<td>(M_w 6.9 &amp; M_w 6.7)</td>
<td>(M_w 7.6)</td>
<td>(M_w 7.9)</td>
<td>(M_w 7.0)</td>
<td>(M_w 7.8 &amp; M_w 7.2)</td>
</tr>
<tr>
<td>Focal depth</td>
<td>19 km (^{7})</td>
<td>25 km &amp; 30 km (^{13})</td>
<td>8-10 km (^{19})</td>
<td>14-19 km (^{26})</td>
<td>13 km (^{31})</td>
<td>8.2 km (^{37})</td>
</tr>
<tr>
<td>Mapped landslides</td>
<td>11,111 (^{8})</td>
<td>4,790 (^{14})</td>
<td>9,272 (^{21})</td>
<td>18,824 of 69,606 (^{27})</td>
<td>23,567 (^{32})</td>
<td>24,915 (^{38})</td>
</tr>
<tr>
<td>Study area</td>
<td>4,000 km(^2)</td>
<td>4,300 km(^2)</td>
<td>10,500 km(^2)</td>
<td>9,800 of 38,000 km(^2)</td>
<td>3,800 km(^2)</td>
<td>29,000 km(^2)</td>
</tr>
<tr>
<td>Landslide mapping</td>
<td>field &amp; aerial reconnaissance, manually digitized on 1:24,000 maps (^{14})</td>
<td>30 m SPOT images (^{14})</td>
<td>20 m SPOT images (^{21})</td>
<td>high-resolution (&lt;15 m) satellite images and air photos (^{21})</td>
<td>satellite imagery with a resolution 0.6 m (^{22})</td>
<td>&lt;0.5 m Worldview-2 Worldview-3 &amp; Pleiades images (^{39})</td>
</tr>
</tbody>
</table>

Citations: \(^{1}\) Colburn et al., 1981; Tsutsumi and Yeats, 1999; \(^{2}\) Parise and Jibson, 2000; \(^{3}\) Meigs et al., 1999; Lave and Burbank, 2004; \(^{4}\) Peul et al., 2007; \(^{5}\) NOAA, 2017; \(^{6}\) National Atlas of United States, 2011; \(^{7}\) Griffith et al., 2016; \(^{8}\) Hauksson et al., 1995; \(^{9}\) Harp and Jibson, 1995; \(^{10}\) Davies et al., 1987; \(^{11}\) Abbott et al., 1997; \(^{12}\) Godard et al., 2010; Liu-Zeng et al., 2011; \(^{13}\) Stevens et al., 1998; \(^{14}\) Meunier et al., 2007; \(^{15}\) Lin et al., 2008; \(^{16}\) Dadson et al., 2003; \(^{17}\) Wu and Kuo, 1999; \(^{18}\) Olsen et al., 2001; \(^{19}\) Shin and Teng, 2001; \(^{20}\) Lee et al., 2001; \(^{21}\) Dadson et al., 2004, \(^{22}\) Burchfiel et al., 1995; \(^{23}\) Ouimet et al., 2007; \(^{24}\) Dadson et al., 2003; \(^{25}\) Liu-Zeng et al., 2011; Li et al., 2016; \(^{26}\) Lee et al., 2008; \(^{27}\) Li et al., 2014; \(^{28}\) Sen et al., 1988, Escuder-Viruete et al., 2007; \(^{29}\) Gorum et al., 2013; Libohova et al., 2017; \(^{30}\) Churches et al., 2014; \(^{31}\) Mercier de Lépinay et al., 2011; \(^{32}\) Harp et al., 2016; \(^{33}\) Hodges et al., 1996; Searle and Godin, 2003; Craddock et al., 2007; \(^{34}\) Lupker et al., 2012; Godard et al., 2014; \(^{35}\) Bookhagen and Burbank, 2006; \(^{36}\) Singh and Singh, 1987; \(^{37}\) Hayes et al., 2015; \(^{38}\) Roback et al., 2018
Figure S3: Finisterre study area with PGA contours from USGS shakemap for the 13th and 25th October 1993 earthquakes, elevation from 1 arcsecond SRTM and landslides from Meunier et al. (2007).
Figure S4: Northridge study area with PGA contours from USGS shakemap, Elevation from 10 m NED and landslides from Harp and Jibson (1996).
Figure S5: Chi-Chi study area with PGA contours from USGS shakemap, elevation from 1 arcsecond SRTM and landslides from Dadson et al. (2004).
Figure S6: Wenchuan study area with PGA contours from USGS shakemap, Elevation from 1 arc second SRTM and landslides from Li et al. (2014). The dashed grey line shows a convex hull around the full inventory of landslides mapped by Li et al. the solid grey line indicates the study area used in this article. The study area was chosen to avoid the large gaps in the 1 arcsecond SRTM data (white patches above).
Figure S7: Haiti study area with PGA contours from USGS shakemap, elevation from 1 arcsecond SRTM and landslides from Harp et al. (2016).

Figure S8: Gorkha study area with PGA contours from USGS shakemap for the 25th April 2015 Gorkha earthquake, elevation from 1 arcsecond SRTM and landslides from Roback et al. (2018).
Supplementary Information 3: Normalised results for slope and upslope contributing area in combination

Figure S9. Two-dimensional plots of landslide hazard, defined as conditional landslide probability $P(L|s,a)$ normalised by study area average landslide probability $P(L)$, where $s$ is local slope normalised by the study area average slope and $a$ is upslope contributing area normalised by the upslope contributing area at which channels begin. Grey cells indicate slope-area pairs with data but with no cells touching a landslide. Fainter colours indicate landslide hazard estimates that do not differ significantly from the study area average.
Figure S10. Comparing the impact of different landslide inventories. Landslide hazard is defined as $P(L|x)/P(L)$ and is estimated from two different landslide inventories for the Wenchuan earthquake, where $x$ is a) local slope, and b) upslope contributing area per unit contour length. Numbers in brackets show study area average landslide probabilities. Results from other earthquakes are shown in faint colours for context. The results from Li et al. (2014) and Xu et al. (2014) for the Wenchuan earthquake are strongly similar.
Figure S11. Comparing the impact of different landslide inventories. Landslide hazard is defined as $P(L|x) / P(L)$ and is estimated from two different landslide inventories for the Wenchuan earthquake, where $x$ is a) skyline angle and b) upslope contributing area per unit contour length. Red bars show histograms of skyline angle and hazard area over the six inventories. Results from other earthquakes are shown in faint colours for context. The results from Li et al. (2014) and Xu et al. (2014) for the Wenchuan earthquake are strongly similar.

Table S3. Area under the ROC curve for the five hazard metrics over the six coseismic landslide inventories. The best performing metric for each inventory is in bold, the second best is in italics.
References


