WHY FROM SPACE?

Predicting the extent of an event and/or damage and obtaining accurate damage data is of crucial importance shortly after an event to guide any rescue efforts.

However:
- Earthquakes and landslides occur frequently in areas that are not easy accessible (rugged terrain)
- Or the event has blocked access to the area and field based analysis is not possible

Therefore:
- Space-based research has good spatial coverage, no need to access terrain but…. Can we derive engineering parameters from satellites?
3 EXAMPLES

1: **Temporal analysis of landslide** behavior shows earthquakes have only short term impact on destabilization of the area (Saba et al., Geomorphology, 2010)

2+3: Earthquake **fault mechanism** is most important parameter for occurrence of earthquake induced landslide (Gorum et al., submitted, 2011, 2012)
On 8 October 2005, a 7.6 Mw earthquake struck the Kashmir area in NE Pakistan. This earthquake triggered numerous landslides and rock falls. Various scientists forecasted long-term major slope failures along the Balakot–Bagh fault line.
According to Dunning et al. (2007): “the seismic shaking leaves an imprint (fractures, tension cracks and brittle deformation of rocks) on the slope stability of the area that may have longlasting effects on the future rates and spatial distribution of landslides”.

Muzaffarabad will experience a great increase in landslide area in the subsequent monsoon season because of the presence of extensive slope cracks (Petley et al., 2006).
LANDSLIDE INVENTORY

Based on:

- 3x fieldwork (2005, 2006, 2007)
- 5 years (2004-2008) of high spatial resolution satellite data
LANDSLIDE INVENTORY

[Map with annotations for different dates and types of landslides indicated by color legend: Rockfall (purple), Slide (Translational and Rotational) (red), Flowslide (yellow), Debris Avalanche (blue), Topple (white), Lateral-spread (brown).]
LANDSLIDE AREA COMPARED WITH RAINFAILL

![Graph showing rainfall and landslide area comparison](image)

- **Freshly triggered landslide area**
- **Total landslide area**
- **Precipitation for each month of the respective year**

*Source: ITC*
CONCLUSION

We conclude that:

after the increased susceptibility of slopes to destabilization by seismic shaking and heavy monsoon seasons further slope destabilization did not last more than two years.

The spatial distribution of landslides remains the same except for few changes in the scarp and toe areas of the landslides.

DOES THIS MAKE SENSE TO YOU?
WHY or WHY NOT
COSICORR FOR SUB-PIXEL DISPLACEMENTS

- Co-registration of Optically Sensed Images and Correlation (CalTech)
- Sub-pixel displacements by sub-pixel correlation
- Requires precise co-registration of image pairs
- Solely based on DEM and platform ancillary data (Quickbird, SPOT and ASTER)


COSICORR RESULTS ON 2005 KASHMIR EARTHQUAKE

Avouac et al., 2006

Kashmir vector field

Movement

Vector field
DE-CORRELATION AT MAJOR LANDSLIDES

A

B

Avouac et al., 2006
SENSITIVITY ANALYSIS ON A SYNTHETIC MODEL

Model settings
- Pixel Resolution
- Amount of Displacement

Software Parameters
- Window Size
- Step Size

Random 1

Random 2

displacement

2000 m

2000 m

1000 m

1000 m

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SENSITIVITY ANALYSIS
SETTING DISPLACEMENT AND IMAGE RESOLUTION

10 px shift

50 px shift

100 px shift

10 px / m

2.5 px / m

1 px / m
SENSITIVITY ANALYSIS
VARIABLES: WINDOW SIZE & STEP SIZE
SENSITIVITY ANALYSIS
RESULTS OF WINDOW SIZE (1)

incorrect

correct
# Sensitivity Analysis
Results of Window Size (2)

<table>
<thead>
<tr>
<th>WINDOW SIZE</th>
<th>4</th>
<th>8</th>
<th>16</th>
<th>32</th>
<th>64</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 2</td>
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<tr>
<td>Test 3</td>
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</tr>
<tr>
<td>Test 4</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

**Displacement (in pixels)**

<table>
<thead>
<tr>
<th>WINDOW SIZE</th>
<th>1</th>
<th>2.5</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Test 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Pixel Resolution (m/pixel)**

- Test 1: 1
- Test 2: 2.5
- Test 3: 5
- Test 4: 10

- Incorrect
- Correct
SENSITIVITY ANALYSIS
RESULTS OF WINDOW SIZE (3)

\[ y = 3.0159x + 2.8889 \]
\[ R^2 = 0.9948 \]
RESULTS ON MUZZAFFARABAD LANDSLIDES
ACCURACY ON MUZZAFFARABAD LANDSLIDES
AND WHAT IS NEXT?

How can you improve these results?

- Different processing – how?
- Remove false anomalies – how?
- Include other data sources – which?
- make better use of field data – how?
EFFECTS OF FILTERING
EARTHQUAKE TRIGGERED LANDSLIDES CHINA & HAITI
LANDSLIDE MAPPING

- What are the criteria for (traditional) landslide susceptibility mapping?

- How do these landslide susceptibility maps compare with reality. What are your experiences?

- Can you think of other, non-traditional, parameters that could play a role?
Traditionally landslide susceptibility mapping is based on the geology and terrain characteristics of the area.

With respect to earthquake induced landslides also the magnitude and distance to epicenter is taken into account.

This is the widely accepted model but there are indications that this model is often having large misfits with reality; landslides are missing, wrongly located or falsely predicted.

Number of landslides seems to very much related to earthquake mechanism and fault dip.

2. WHERE IS THE LANDSLIDE?
RELATION MECHANISM VS OCCURRENCE

Faulting mechanism / Magnitude (Mw)
- Thrust/Reverse = 5.5 - 6.0
- Normal = 6.1 - 7.0
- Strike-slip = 7.1 - 8.0

Number of coseismic landslides

Dip angle of fault, \( \theta \) (degrees)
2008 Wenchuan, China Mw 7.9 earthquake

Thrust fault in SW changing to strike-slip in NE

We mapped 60,000 landslides

Landslide density much higher in SW, very low in NE
RELATION WITH TOPOGRAPHY

- Terrain deformation doesn’t show high correlation with landslide occurrence

- Topography and internal relief are not explaining the landslide distribution

- Not shown here but similar geological units in similar terrain at both sides of the fault show different landslide density
Thick black line and brown shading are normalized coseismic landslide densities, computed for 60-m bins. Thin dashed black lines are ruptured fault sections inferred from inversion of GPS-InSAR data; grey boxes show fault-rupture projections onto ground surface.
CONCLUSION

In summary, our results lend strong support to the notion that the distribution of coseismic landslides is controlled by fault type and coseismic slip (rates)

The effect of magnitude and epicenter distance is of less importance

Likewise, topography and lithology play subordinate roles; variations in rock type or relief insufficiently explain the pattern of coseismic landslides

Modifications required to existing models of earthquake-triggered landslide susceptibility solely based on empirical relationships
3. PREDICTION OF EARTHQUAKE INDUCED DAMAGES
EARTHQUAKE SITE AMPLIFICATION

- **SOURCE EFFECTS**
  - Hypocenter
  - Causative Fault

- **MEDIUM EFFECTS**
  - Seismic Waves

- **SITE EFFECTS**
  - Topographic effects
  - Soil depth effects
  - Geologic effects
SOIL DEPTH IS INFLUENCED BY...

- Topography
- Geomorphology
- Geology
- Landuse

→ Factors addressed following a Remote Sensing & GIS based approach
SOIL DEPTH SAMPLES AND RESISTIVITY PROFILES
RESISTIVITY IMAGING
## TOTAL AVAILABLE DATA

### Number of soil depth samples and resistivity profiles

<table>
<thead>
<tr>
<th>Samples at exposed bedrock</th>
<th>Resistivity Profiles (R.P)</th>
<th>Interpreted soil depth from R.P</th>
<th>Total soil depth samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>109</td>
<td>24</td>
<td>60</td>
<td>169</td>
</tr>
</tbody>
</table>

### Distribution of soil depth samples in different landforms

<table>
<thead>
<tr>
<th>Landforms</th>
<th>Outcrop samples</th>
<th>Samples from R.P</th>
<th>Total</th>
<th>% of Samples</th>
<th>% of covered area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvial Fan</td>
<td>31</td>
<td>25</td>
<td>56</td>
<td>33.1</td>
<td>30.5</td>
</tr>
<tr>
<td>Flood Plain</td>
<td>39</td>
<td>20</td>
<td>59</td>
<td>34.9</td>
<td>32.4</td>
</tr>
<tr>
<td>River Terrace</td>
<td>39</td>
<td>15</td>
<td>54</td>
<td>32.0</td>
<td>20.8</td>
</tr>
<tr>
<td>River Bed</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16.3</td>
</tr>
</tbody>
</table>
VALIDATION OF PREDICTED SOIL DEPTH

[Graph showing the comparison of predicted and actual regolith thicknesses with different markers for River Terrace, Flood Plain, and Alluvial Fan, and an RMSE of 0.26 m]
Soil depth variation along landform boundaries
RELATION DAMAGE WITH SOIL DEPTH

\( R^2 = 0.38 \)

\( R^2 = 0.46 \)
ALTERNATIVE USING OBJECT BASED CLASSIFICATION

Same area

Use of 30m resolution
ASTER digital
elevation model

Classification based
on terrain
characteristics like
slope, curvature, height

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OBJECT BASED TERRAIN CLASSIFICATION
COMPARISON WITH DAMAGE DATA
### CLASSES VS DAMAGE COMPARISON

<table>
<thead>
<tr>
<th>Damage Intensity</th>
<th>Terrain units</th>
<th>Total</th>
<th>Producer accuracy</th>
<th>User accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basins</td>
<td>Piedmont</td>
<td>Mountains</td>
<td></td>
</tr>
<tr>
<td>Severe</td>
<td>63 (21.82)</td>
<td>9 (1.55)</td>
<td>0</td>
<td>72</td>
</tr>
<tr>
<td>Moderate</td>
<td>10 (3.86)</td>
<td>18 (29)</td>
<td>1 (0.99)</td>
<td>29</td>
</tr>
<tr>
<td>Less</td>
<td>0</td>
<td>0</td>
<td>2 (1.33)</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>73</td>
<td>27</td>
<td>3</td>
<td>103</td>
</tr>
</tbody>
</table>

Overall accuracy = 81%

- Extreme classes are well predicted
- Overall accuracy is high, especially for the highest damage classes
- Classes are indicative of actual damage → indicative of seismic amplification → indicative of earthquake engineering properties
Classes are transformed into earthquake engineering parameters

Near-surface velocity ($Vs_{30}$) is well established earthquake engineering parameters

Can be used as input for future seismic hazard models + damage assessment after new earthquake
CONCLUSION

- Deriving soil depth from remotely sensed data works very well
- Link with damage data works to some extent, other factors influence result:
  - Other site effects like topography
  - Building variation
  - Different scales of analysis

- Translation into engineering parameters is possible

- OVERALL: Remote sensing can provide unique insights due to spatial and temporal extent
EARTHQUAKE AND LANDSLIDE ENGINEERING FROM SPACE

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