Controls, timing, and characteristics of submarine landslides in the Mediterranean area

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PRESENTATION STRUCTURE

✓ The Mediterranean Sea: a geohazard perspective
✓ Submarine landslides in the Mediterranean Sea
   ✓ Areal distribution and controls on offshore failure development
     ✓ Tectonics
     ✓ Seismicity
     ✓ Fluid seepage
     ✓ Basement structure
   ✓ Dynamic indicators: displacement and typology
   ✓ Magnitude indicators: area, volume and scars
   ✓ Timing of failures
   ✓ Tsunamigenic potential
✓ Conclusions
✓ Open questions
WHY THE MEDITERRANEAN SEA

- Very densely-populated coastline: 160 million inhabitants sharing 46,000 km of coastline (3.5 inhabitants per m of coastline).

- World's leading holiday destination, receiving up 30% of global tourism and an average of 135 million visitors annually; this is predicted to increase to 235-350 million tourists by year 2025 (European Environmental Agency - EEA).

“By 2025, the annual crowd will soar to anywhere from 235 to 350 million tourists, according to the EEA.”


EEA web site http://www.eea.europa.eu
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WHY THE MEDITERRANEAN SEA

Very high density of seafloor structures / increasing use of the seafloor:

✓ Infrastructures (oil, windmills, telecommunications, pipelines, ...)
✓ Exploitation of mineral and energy resources
✓ Waste disposal

A study on behalf of the Submarine Cable Improvement Group shows 25% of all faults are caused by natural hazards such as submarine earthquakes, density currents and extreme weather.

Mediterranean Fibre Cable Cut - a RIPE NCC Analysis http://www.ripe.net/
Analysis by the RIPE NCC Science Group with contributions from Roma Tre University. Editors: Rene Wilhelm, Chris Buckridge
WHY THE MEDITERRANEAN SEA

• Rich record of historical tsunamis

National Geophysical Data Center / World Data Center (NGDC/WDC) Historical Tsunami Database, Boulder, CO, USA. (Available at http://www.ngdc.noaa.gov/hazard/tsu_db.shtml)
WHY THE MEDITERRANEAN SEA

• Some tsunamis related to submarine landslides (up to 15%)
• Small dimensions ⇒ close proximity of tsunami sources and impact areas.

Compared to large oceanic basins, the Mediterranean Sea has a very high vulnerability to damage caused by submarine geohazards.

1783 Scilla coastal landslide (Italy)
1908 Messina (Italy)
1956 Central Aegean Sea (Greece)
1979 Nice airport landslide (France)
1999 Değirmendere coastal landslide, (Turkey)
2002 Stromboli volcano landslide (Italy).

National Geophysical Data Center / World Data Center (NGDC/WDC) Historical Tsunami Database, Boulder, CO, USA. (Available at http://www.ngdc.noaa.gov/hazard/tsu_db.shtml)
AIMS

✓ Understand the magnitude, frequency and controls on submarine slope failure at the scale of a large marine basin

✓ Better characterize the potential for extreme geohazards in the Mediterranean
Submarine landslides in the Mediterranean Sea
R. Urgeles et al.: Submarine landslides in the Mediterranean Sea

Areal distribution

Submarine landslides occur in very different geological settings of the Mediterranean continental margins often at depths > 1000m on slopes of < 2°

Noticeable correlation between known failure events and available high/resolution geophysical data.

The catalogue of submarine slope failures is still largely uncomplete (specially for the North-African margin).
Relation to the geological structure

- Two clusters of known major submarine landslides → aseismic margins (Ebro, Rhone, Nile).
- The most tectonically active area (The Hellenic Arc) has a relatively low density of known events.
- The deformation fronts of the Mediterranean and Calabrian ridges host few submarine landslides.
Relation to the margin hydrogeology

- Active fluid seepage structures often related to tectonics
- Large landslides occur in areas of active fluid seeping and Messinian salt tectonics.
Relation to the margin hydrogeology

Ana slide (0.14 km$^3$ $\rightarrow$ 3.5 x 1.5 km), Holocene

Importance of fluid flow systems and overpressure generation $\rightarrow$ common observation
Relation to the margin hydrogeology

Berndt et al., EPSL, subm.
 Fluid escape through erosional features on MES
 Fluid pathway controlled by permeability layering and tectonics
 Overpressure develops at shallow depth due gas saturation and reduction in total stress? (gas exsolution)

Berndt et al., EPSL, subm.
Swath bathymetry of the BIG’95 debris flow area with location of the landslide boundaries.

- our study.
- Baraza et al. (1990).
Relation to the margin hydrogeology

PGA according to published strong ground motion – attenuation relations
Relation to the margin hydrogeology

Drained back-analysis:

FS hydrostatic: 5.01

→ Pressure gradient: ~8 kPa/m ($R_u=0.7$)
Relation to basement structure
Relation to basement structure

Structure map of the volcanic dome

Seismic reflection profiles
Dynamic characteristics: typology

Typology

- Debris Avalanche
- Debris Flow
- Deep-seated failure
- Glide
- Mass Failure
- Mass Transport
- Mass Wasting
- Megaturbidite
- Olistrome
- Slide
- Slump

Graph showing the frequency and volume of different typologies.
Dynamic characteristics: typology

The ratio H/R of submarine landslides of the same volume exhibit an apparent friction coefficient some 10 times lower → Hydroplanning
Magnitude characteristics: area

- Gulf of Mexico ~27%
- New Jersey Margin ~9.5
- California Margin ~7%
- Oregon Margin ~3%

- Canary Basin ~10%

- Area ranging from a few squared km to about 1000 km²
- Little erosion, wide-spread slope hydrological conditions → large failures

8% of Mediterranean seafloor is occupied by mass gravity-flows.
Magnitude characteristics: volume

- Volume up to 1000 km$^3$

<table>
<thead>
<tr>
<th>Location</th>
<th>Volume (km$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saint Helens, WA</td>
<td>0.003</td>
</tr>
<tr>
<td>Saint-Jean-Vianney, QC</td>
<td>0.007</td>
</tr>
<tr>
<td>Usoi, TJ</td>
<td>0.002</td>
</tr>
<tr>
<td>Frank Slide, BC</td>
<td>0.03</td>
</tr>
<tr>
<td>Hope Slide, BC</td>
<td>0.047</td>
</tr>
<tr>
<td>Pufu, CH</td>
<td>0.45</td>
</tr>
<tr>
<td>Vajont, IT</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Magnitude characteristics: volume

Assuming that the cumulative-volume data conforms to a Pareto distribution

\[ F(x) = \text{prob}(x) = \frac{\theta x^\theta}{x^\theta + 1} \]

\[ x_0 = 0.000007 \text{ km}^3 \]
\[ \theta = 0.832 \]

Landslide with probability of observation of:
- 10\% 0.0145 km$^3$
- 25\% 0.0088 km$^3$
- 50\% 0.0060 km$^3$
- 75\% 0.0048 km$^3$

A landslide of 1 km$^3$ has a probability of observation of $4.2 \times 10^{-3}$
Magnitude characteristics: scars

Headwalls are generally less than 20 km long, but may reach 75 km and are involve sequences up to 300 m thick.
Timing of failure

$n_{\text{radioisotopic}}: 59$

$n_{\text{epoch}}: 437$

Landslide emplacement during the last de-glaciation
Timing of failure

Recurrence
(oldest event within a volume bin / # dated events within the same volume bin)
Consequences

- Slide motion → Watts and Grilli (2002)
- Tsunami generation and propagation → Geowave
  - TOPICS initial free surface elevation and water velocities derived from multivariate, semi-empirical curve fits
  - FUNWAVE long wave propagation model based on the Boussinesq approximation of wave dynamics (Wei et al., 1995; Wei and Kirby, 1995).

BIG’95 mid-size 26 km³ slide

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean $z_0$</td>
<td>1275 m</td>
</tr>
<tr>
<td>Mean angle</td>
<td>1.5°</td>
</tr>
<tr>
<td>Length</td>
<td>8.8 km</td>
</tr>
<tr>
<td>Thickness</td>
<td>250 m</td>
</tr>
<tr>
<td>Width</td>
<td>11.1 km</td>
</tr>
<tr>
<td>Bulk density</td>
<td>1.7 g/cm³</td>
</tr>
<tr>
<td>$a_0$</td>
<td>0.0636 m/s²</td>
</tr>
<tr>
<td>Terminal velocity</td>
<td>48.348 m/s</td>
</tr>
<tr>
<td>Characteristic motion</td>
<td>37 km</td>
</tr>
<tr>
<td>Characteristic time</td>
<td>760 s</td>
</tr>
<tr>
<td>Tsunami wavelength</td>
<td>8.5 km</td>
</tr>
<tr>
<td>Distance traveled in $t_0$</td>
<td>16 km</td>
</tr>
<tr>
<td>Max. Froude number</td>
<td>0.43</td>
</tr>
</tbody>
</table>
Consequences

BIG’95 mid-size 26 km³ slide → max. Sea surface elevation
Consequences

$\lambda_0$: characteristic wavelength

Tsunami Wavemaker model (Watts et al. 2003: NHESS)

$$\lambda_0 \equiv t_o \sqrt{g d} \approx 3.87 \sqrt{\frac{bd}{\sin \theta}}$$
Consequences

$\eta_{2d}$: characteristic 2D amplitude

\[
\eta_{2d} \approx 0.2139 \ T \left( 1 - 0.7458 \sin \theta + 0.1704 \sin^2 \theta \right) \left( \frac{b \sin \theta}{d} \right)^{1.25}
\]

Tsunami Wavemaker model (Watts et al. 2003: NHESS)
CONCLUSIONS:

✓ Incomplete catalogue!!
✓ Need to standardize the information being published
✓ Tectonically active margins $\rightarrow$ numerous but small failures.
✓ Passive margins with large sediment supply $\rightarrow$ larger slope failures; large overpressure necessary for failure; unfrequent process
✓ Landslides originate in water depths exceeding 1000 m on slopes of 2º.
  ✓ Continental rise is a place of high slope instability
✓ Highly mobile events, many structures can be put at risk along their path
✓ Little is known for age of the failure events
  ✓ 47/532 ~ accurate age determinations.
  ✓ 437 reported with an epoch (difficult relation trigger - environmental factors)
  ✓ Large amount of Holocene events $\rightarrow$ climate induced stress changes
    (sedimentary load, sea level, bottom temperature effect on fluid flow, gas hydrate and gas systems)
✓ MES and salt distribution $\rightarrow$ major condition for fluid migration pathways
✓ Basement structure and consolidation couple to control location of slope failure
✓ Tsunamis $\rightarrow$ major consequence and potential geohazard
  ✓ Active margins $\rightarrow$ freq., small landslide tsunamis
  ✓ Passive margins $\rightarrow$ unfreq., large landslide tsunamis (preparedness, resilience)
Thanks!