PFC2D modelling of sinkhole clusters in karstic depressions

Djamil Al-Halbouni\textsuperscript{1,2}, Sacha Emam\textsuperscript{3}, Eoghan P. Holohan\textsuperscript{4}, Abbas Taheri\textsuperscript{5}, Martin P.J. Schöpfer\textsuperscript{6}, Torsten Dahm\textsuperscript{1,2}

\textsuperscript{1}Helmholtz Centre - German Research Centre for Geosciences (GFZ), Physics of Earthquakes and Volcanoes, Telegrafenberg, Potsdam 14473, Germany.
\textsuperscript{2}University of Potsdam, Institute of Geosciences, P.O. Box 601553, Potsdam-Golm 14415, Germany.
\textsuperscript{3}Itasca Consultants S.A.S., Écully, France.
\textsuperscript{4}UCD School of Earth Sciences, University College Dublin, Belfield, Dublin 4, Ireland.
\textsuperscript{5}School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, South Australia 5005, Australia.
\textsuperscript{6}Department for Geodynamics and Sedimentology, University of Vienna, Athanstrasse 14, A-1090, Vienna, Austria.
**Sinkholes in general**

*Sinkholes are enclosed depressions of the surface and appear in terrain prone to dissolution and subrosion, like limestone or salt karst.*

©Wikimedia commons.
Sinkholes at the Dead Sea
Shrinking of the lake
Sinkholes at the Dead Sea

Ghor Al-Haditha

Aerial photographs

Sinkhole formation rate

©Watson et al. 2018
Photogrammetry and field analysis

Mud-flat with evaporites

Alluvial fan sediments

Orthophoto 2014 on satellite image 2011
Photogrammetry and field analysis

Alluvial gravel & sand  Lacustrine mud  Lacustrine evaporites

Individual dry sinkholes

Multiple sinkholes in depressions

Sinkholes with springs

material mixture  material mixture
Photogrammetry and field analysis

Morphological differences of individual sinkholes

Digital Surface Model 2014
Photogrammetry and field analysis

Morphological differences of individual sinkholes

Digital Surface Model 2014
Photogrammetry and field analysis

Sinkhole clusters and large-scale depressions

Mod. after Watson et al. 2018
Distinct Element Modelling
Sinkhole modelling approach

Modelling setup with PFC2D-V5
Model resolution: H = 400 m, W = 400 m, R = 0.32 m

Material parameters
- **Salt**
  - UCS: 1.23-1.54 MPa
  - UTS: 0.31-0.43 MPa
  - Modulus: 1106 ± 126 MPa
- **Alluvium**
  - UCS: 0.52-0.92 MPa
  - UTS: 0.18-0.24 MPa
  - Modulus: 174 ± 25 MPa
- **Mud**
  - UCS: 0.06-0.25 MPa
  - UTS: 0.01-0.2 MPa
  - Modulus: 84 ± 20 MPa
DEM models of individual sinkhole formation

[Diagrams showing different models of sinkholes at various depths (20m, 30m, 40m) with labels for Mud, Alluvium, and Salt. Each depth level has a color key for maximum shear strain (ymax).]
DEM models of multiple sinkholes & large-scale depressions

Strong overburden

Weak overburden

Alluvium Mud Salt Mud Alluv Mud Salt Alluv
DEM models of multiple sinkholes & large-scale depressions

Constant subrosion

Differential subrosion

Maximum shear strain snapshots prior to collapse.
Comparison with morphological data

Individual sinkholes

Interpreted as growth stages.
Comparison with geophysical data

Field estimation by shear wave reflection seismics

Simulated shear-wave velocities

Initial

Post-collapse

ELVIS landstreamer unit
Comparison with geophysical data

Field estimation by shear wave reflection seismics

Simulated shear-wave velocities

Initial

Post-collapse

Thesis chapter V
1) Sinkhole morphologies & development in space & time:
   • Clustered, elliptical sinkholes within large-scale depressions
   • Deeper & narrower in alluvium, wider & shallower in mud/salt-flat

2) Mechanical development of sinkholes & clusters:
   • Calibrated DEM approach for realistic sinkhole simulation
   • Good agreement with morphometrics & structural features
   • Formation is controlled by:
     • material strength in both overburden & cavity host material,
     • depth, geometry & relative speed of material removal
     • developed stress pattern in the subsurface
   • The presence of a hard/soluble interlayer like salt under a mud layer is not necessary to reproduce the sinkhole morphology observed in the Gor Al-Hadita area

3) Geophysical parameters:
   • Good agreement of seismic velocities reflecting the downward growth of the subrosion zone
Thank you
Publications

DEM:


Morphology:


Geophysics: