Wednesday, 19 April 2023—February 2023 Mw 7.8 Earthquake Sequence in Turkey

Presenting author is indicated in bold.

Time	*201A/B*
8:00 AM	The Destructive Earthquake Sequence of February 06, 2023, in South-Central Türkiye and Northern Syria: Initial Observations and Analyses. **Mai, P.**, Aspiotis, T., Anwar, T., Castro-Cruz, D., Li, B., *et al.*
8:15 AM	Aftershock Sequence of Türkiye Doublet Illuminates Complexity of Fault Structure and Delineates Frictional Heterogeneity. Zhou, Y., **Ghosh, A.**
8:30 AM	Evidence of Early Supershear Transition in the Mw 7.8 Kahramanmaraş Earthquake From Near-Field Records. **Elbanna, A.**, Abdelmeguid, M., Rosakis, A.
8:45 AM	Rapid Dynamic Rupture Modeling of the February 6, 2023, Kahramanmaraş, Turkey-Syria Earthquake Doublet. Gabriel, A., **Ulrich, T.**, Marchandon, M., Biemiller, J., Rekoske, J.
9:00 AM	Finite Fault Forward Modeling of the Mw 7.8 and 7.7 February 2023 Earthquakes Near the Turkey-Syria Border and Aftershock Point Source Modeling Using a Regional 3D Velocity Model for the Middle-East. **Rodriguez Cardozo, F. R.**, Sawade, L., Orsvuran, R., Bozdag, E., Braunmiller, J., *et al.*
9:15–10:30 AM	Poster Break
10:30 AM	February 6, 2023 Kahramanmaraş Earthquake Sequence: Preliminary Observations Along the Surface Rupture and Slip Distribution of the Mw 7.5 Ekinözü Earthquake. **Akçiz, S. O.**, Sançar, T., Kıray, H. N., Zabcı, C., Köküm, M., *et al.*
10:45 AM	Rapid Surface Rupture Mapping of the 6 February 2023 Kahramanmaraş Earthquake Sequence to Support Response Efforts. **Reitman, N.**, Briggs, R. W., Barnhart, W. D., Thompson Jobe, J. A., DuRoss, C. B., *et al.*
11:00 AM	3D Near-Field Surface Deformation, Stress and Friction of the 2023 Mw 7.8 and Mw 7.6 Kahramanmaras Earthquakes Measured by Alos-2, Sentinel-1 and Sentinel-2 Pixel Offsets. **Milliner, C. W. D.**, Avouac, J., Lindsay, D., Güvercin, S., Konca, O., *et al.*
11:15 AM	Field Evidence on Seismo-tectonic and Seismo-gravitational Structures Related with the February 2023 Earthquake Sequences in Türkiye. **Sümer, Ö.**, Drahor, M. G., Ongar, A., Eski, S., Tepe, Ç., *et al.*
11:30 AM	Non-Uniqueness Dilemma in the Kahramanmaras Tsunami Source Solutions at Different Frequencies: Hint for Excitation by Transient Rayleigh Waves From a Strike-Slip Rupture. **Salaree, A.**
12:00–2:00 PM	Awards Luncheon and Presidential Address
2:00 PM	U.S. Geological Survey's Hazard and Impact Assessment of the 2023 Türkiye Earthquake Sequence. **Wald, D. J.**, Quitoriano, V., Thompson, E. M., Goldberg, D., Xu, S., *et al.*
2:15 PM	Geotechnical Characteristics of Golbasi (Adiyaman) Soils Exhibiting Large Deformations on February 06, 2023 Earthquakes. **Ozden, G.**, Tatar, O., Kartal, B., Atlı, O., Yukselen Aksoy, Y.
2:30 PM	Near-Fault Ground Motion Modeling Due to the 2023 M7.8 Kahramanmaras Earthquake and Impacts on Local Buildings. **Gu, C.**, Wu, P., Zhong, Y., Kang, B., Prieto, G. A., *et al.*
2:45 PM	STUDENT: Dynamic Site Response Analysis of Adiyaman Golbasi Soils During February 06, 2023 Kahramanmaras Earthquakes. **Kİlİc, B.**, Ozden, G., Kartal, B., Yukselen Aksoy, Y., Bozdag, O.
3:00 PM	Months-Long Preparation of the 2023 Mw 7.8 Kahramanmaraş Earthquake, Türkiye. Kwiatek, G., **Martínez-Garzón, P.**, Becker, D., Dresen, G., Cotton, F., *et al.*
3:15 PM–4:30 PM	Poster Break
4:30 PM	Landslides Triggered by the February 6, 2023 Kahramanmaraş Earthquake Sequence. Görüm, T., Tanyas, H., Karabacak, F., Yilmaz, A., Suzen, L., Burgi, P., **Allstadt, K.**
4:45 PM	Causes of the Earthquake Damage of Buildings in the Aftermath of the February 6, 2023 Earthquake. Bozdağ, Ö., **Tanarslan, H.**
5:00 PM	Artificial Neural Networking and Statistical Analysis of Turkey's Earthquake 2023. **Manna, S.**, Pandey, M.
5:15 PM	Near-Real-Time Estimates of Fatalities Due to the M7.8 Earthquake on 6 February 2023 in Turkey. **Wyss, M.**, Speiser, M.
5:30 PM	Science Communication During an Actively Unfolding Disaster. **Pascale, A.**
6–7 PM	Joyner Lecture
7–8 PM	Joyner Reception

February 2023 Mw 7.8 Earthquake Sequence in Turkey (Posters)

148. Characterization of Source, Path and Site Effects on Ground Motions From the 2023 Kahramanmaraş, Türkiye, Earthquake Sequence. Parker, G. A., **Baltay, A. S.**, Thompson, E. M., Çelebi, M., Aagaard, B. T., *et al.*
144. Coastal Effects of the Kahramanras Turkey-Syria Twin Earthquakes of February 6th, 2023: Recommendations for Using Geospatial Analysis Tools to Predict Abnormal Water Impact. **Barberopoulou, A.**, Sanon, C., Asadi, A.
141. STUDENT: Dynamic Rupture Models for the 2023 M7.8 Turkey Earthquake Along the East Anatolian Fault Zone. **Marschall, E.**, Douilly, R., Wu, B., Funning, G.
151. Establishment and Success of the AFAD Earthquake Clearinghouse and Reconnaissance Data Collection Efforts Following the Mw 7.7 and Mw 7.6 Kahramanmaras Earthquakes in Eastern Turkey. **Cakir, R.**, Tatar, O., Mandal, H., Sezer, Y., Celik, D., *et al.*
146. STUDENT: Flow Type Deformations of Onshore Soils in Adiyaman-Golbasi During February 06, 2023 Kahramanmaras Earthquakes. **Tatar, O.**, Ozdag, O., Bulgurcu, A., Yerli, B., Ozden, G., *et al.*
149. Investigation of Damages in Schools and Buildings in Adıyaman Gölbaşı After February 6, 2023 Earthquake. **Bozdağ, Ö.**, Tanarslan, H.
143. Performance Evaluation and Updates to a Geospatial Liquefaction Model Using Observational Data From the February 2023 Earthquake Sequence in Turkey and Syria. **Baise, L. G.**, Sanon, C., Zhan, W., Barberopoulou, A., Verma, N., *et al.*
150. The Operational Service of Aristotle-Eenhsp for the February 6, 2023 Earthquakes in Turkey-Syria. **Michelini, A.**, Tolea, A., Olivieri, M., Lentas, K., Turhan, F., *et al.*
139. STUDENT: Preliminary Analysis and Model of the Complex Rupture Dynamics Behind the Mw 7.8 and Mw 7.5 Kahramanmaraş Earthquakes in Turkiye. **Zaccagnino, D.**, Stabile, T. A., Tan, O., Telesca, L., Akinci, A., *et al.*
135. Rapid Characterization of the 2023 Kahramanmaraş, Türkiye, Earthquake Sequence at the USGS National Earthquake Information Center. **Goldberg, D. E.**, Taymaz, T., Reitman, N. G., Hatem, A. E., Yolsal-Çevikbilen, S., *et al.*
142. Reconnaissance Geological Observations of the February 06, 2023 Kahramanmaraş, Türkiye Earthquakes. **Koehler, R. D.**, Yildirim, C., Clahan, K. B., Kozaci, O., Altunel, E.
138. STUDENT: Rupture Process of the February 2023 Mw 7.8 Earthquake Sequence in South-Central Türkiye and Northwestern Syria From Teleseismic P-Wave Data. **Suhendi, C.**, Li, B., Li, X., Palgunadi, K., Liu, J., *et al.*
136. Seismic Activity and Aftershock Potential of the 6 February 2023 Mw 7.7 and Mw 7.6 Kahramanmaras Earthquake Sequence in Eastern Turkey. **Utku, M.**, Cakir, R., Softa, M., Sozbilir, H.
137. Sequence-Specific Updating of European ETAS Model: Application to the 2023 Türkiye-Syria Earthquake Sequence. Han, M., **Mizrahi, L.**, Dallo, I., Wiemer, S.
147. Source, Path, and Site Effects on the Peak Velocity From the 2023 Pazarcik, Turkey Mainshock. **Sung, C.**, Abrahamson, N., Gülerce, Z., Akbas, B.
140. Sub- and Super-Shear Ruptures During the February 6, 2023 Mw 7.8 and Mw 7.6 Earthquake Doublet in Se Türkiye From Joint Inversion of Seismic and Geodetic Data. **Melgar, D.**, Taymaz, T., Ganas, A., Crowell, B. W., Mildon, Z., *et al.*

Abstracts of the Annual Meeting

February 2023 Mw 7.8 Earthquake Sequence in Turkey

Oral Session • Wednesday 19 April • 08:00 AM Pacific
Conveners: Xyoli Pérez-Campos, xyoli@igeofisica.unam.mx, Universidad Nacional Autónoma de México and Elizabeth Vanacore, elizabeth.vanacore@upr.edu, University of Puerto Rico, Mayagüez

The Destructive Earthquake Sequence of February 06, 2023, in South-Central Türkiye and Northern Syria: Initial Observations and Analyses

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On February 6, 2023, two powerful earthquakes of magnitude 7.8 and 7.6 rocked south-central Türkiye and northern Syria, strongly affecting the regions around Gaziantep, Kahramanmaraş, Malatya, and Hatay. The epicenter of the first mainshock is located close to the East Anatolian Fault (EAF), while the second large earthquake 9 hours later initiated ~90 km north of the first mainshock on an east-west trending fault. Aftershocks delineate fault lengths of ~360 km and ~180 km, respectively. At the time of writing, the death toll surpasses 40,000 victims, rendering these events the deadliest earthquakes in Turkey since the 1939 rupture on the eastern North Anatolian Fault (NAF).

We collect seismic and satellite data to perform first-order analyses on surface-fault offsets, space-time evolution of the ruptures, and recorded ground-motions to help shed light on the reason for the destruction caused by these two earthquakes. The first event started on an EAF-branch and then ruptured the EAF bilaterally, lasted for ~80 sec and created surface-offsets of up to 7 m. The second event had a duration of ~40 sec, ruptured bilaterally and generated up to 8 m surface displacements. Both events are characterized by abrupt rupture cessation, generating strong stopping phases that may have contributed to the observed high shaking levels. In addition, directivity effects and local site amplifications are responsible for very large ground motions locally.

Aftershock Sequence of Türkiye Doublet Illuminates Complexity of Fault Structure and Delineates Frictional Heterogeneity

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Two back-to-back damaging earthquakes hit Türkiye on February 6^{th}, 2023. A Mw 7.8 earthquake ruptured southwestern part of East Anatolian Fault Zone (EAFZ). And a Mw 7.6 event struck about 10 hours later in Sürgü fault, north of EAFZ. Sadly, this doublet has caused severe structural damage in Türkiye and Syria with more than 55,000 fatalities.

Both events are producing prolific aftershock activity illuminating fault geometry and structures that may have played important roles in earthquake nucleation and rupture propagation. We use 44 broadband stations covering the aftershock region and analyze continuous seismic data for the entire month of February, including 5 days before the mainshocks and 23 days after. We apply a streamlined workflow containing Phase picking, Association, Location and Matched filter (PALM) [Zhou et al., 2021] to produce a high resolution earthquake catalog with increased detectability and relocated events. Overall, this catalog contains about 28,000 events, nearly 3 times more compared to the one produced by the Disaster and Emergency Management Presidency of Türkiye. Aftershock distribution lights up the faults involved in this sequence distinctly with some intriguing features. It varies significantly along strike and dip – both in the EAFZ and the Sürgü fault. Southwestern end of the EAFZ shows relatively low activity and diffuse seismicity while northeastern end is characterized by intense clustered seismicity. In the Sürgü fault, seismicity patterns west and east of the hypocenter are distinctly different with western part being more vigorous with streaks of aftershock activities. Seismicity also delineates significant change in fault strike and smaller branches joining the main, much longer fault lines. By the time we present this work, we plan to use this catalog to train a model based on machine learning, and produce an earthquake catalog applying artificial intelligence. In summary, distribution of aftershocks is defining complexities in the fault structures and frictional variations along the fault that may be controlling the earthquake production in this sequence.

Evidence of Early Supershear Transition in the Mw 7.8 Kahramanmaraş Earthquake From Near-Field Records

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The Mw7.8 Kahramanmaraş Earthquake was larger and more destructive than what had been expected for the tectonic setting in Southeastern Turkey. By using near-field records we provide evidence for early supershear transition on the splay fault that hosted the nucleation and early propagation of the first rupture that eventually transitioned into the East Anatolian fault. The two stations located furthest from the epicenter show a larger fault parallel particle velocity component relative to the fault normal particle velocity component; a unique signature of supershear ruptures that has been identified in theoretical and experimental models of intersonic rupture growth. The third station located closest to the epicenter, while mostly preserving the classical sub-Rayleigh characteristics, it also features a small supershear pulse clearly propagating ahead of the original sub-Rayleigh rupture. This record provides, for the first time ever, field observational evidence for the mechanism of intersonic transition. By using the two furthest stations we estimate the instantaneous supershear rupture propagation speed to be ~1.55 C_s and the sub-Rayleigh to supershear transition length to be around ~ 19.45 km, very close to the location of the station nearest to the epicenter. This early supershear transition might have facilitated the continued propagation and triggering of slip on the nearby East Anatolian Fault leading to amplification of the hazard. The complex dynamics of the Kahramanmaraş earthquake warrants further studies.

Rapid Dynamic Rupture Modeling of the February 6, 2023, Kahramanmaraş, Turkey-Syria Earthquake Doublet

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The dynamically complex February 6, 2023, Turkey-Syria Earthquake sequence ruptured an unexpected set of variably oriented neighboring fault segments, complicating data-driven efforts to image and model the source processes of these devastating earthquakes. We present rapid 3D dynamic rupture simulations, verified against geodetic and seismic observations, illuminating the mechanics and dynamics of rupture complexities observed in the Kahramanmaraş doublet, which involved an initial Mw 7.8 event followed

by a Mw 7.7 event ~100 km to the NNE. We provide mechanically consistent explanations of observed subshear and supershear rupture speeds, multiple slip episodes, strong ground motion pulses, and fault system interaction.

We reconcile regional seismo-tectonics, rupture dynamics, and ground motions up to 1 Hz in a geometrically complex network of ten curved fault segments subject to a heterogeneous regional stress field. We analyze the factors contributing to the doublet's dynamics and regional ground motions, including fault geometry and the relative roles of static and dynamic triggering. The doublet's linked dynamic rupture scenarios each match seismo-geodetic observations and observed fault-system interactions. The Mw 7.8 event involved delayed, dynamically unfavorable backward branching from a steeply intersecting splay fault, which did not necessarily require supershear speeds. The asymmetric dynamics of the bilateral Mw 7.7 event arise from variations in prestress, fracture energy, and relative fault strength, which we discuss in relation to regional seismo-tectonics. The dynamics of the second event are complicated by the 3D mainshock stressing, which was too low for instantaneous dynamic triggering during the mainshock. We demonstrate that rapidly developed dynamic rupture models can explain unexpected fault system mechanics shortly after large earthquakes. Our results may help inform rapid post-event hazard assessment efforts following future earthquakes and constrain short- and long-term mechanical interactions between faults of the Eastern Anatolian Fault system and complex multi-fault systems worldwide.

Finite Fault Forward Modeling of the Mw 7.8 and 7.7 February 2023 Earthquakes Near the Turkey-Syria Border and Aftershock Point Source Modeling Using a Regional 3D Velocity Model for the Middle-East

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Two large and devastating earthquakes struck the Turkey-Syria border region on February 6th 2023 in and on the Eastern Anatolian fault rupturing various faults in the Anatolia, Nubia, Arabia triple junction region. The mainshock, a Mw 7.8 at 01:18 UTC, was followed by a Mw 7.7 event at 10:25 UTC. Based on the USGS finite fault model, the total rupture lengths for each event were over 300 km and ~150 km, respectively, with maximum slip for each exceeding 11 m. The finite fault models for each event suggest significant slip on several faults with complex slip distributions and source time histories as expected for such large earthquakes. Despite their complexity, the models do not predict certain observed ground motions well. We used a regional 3D velocity model (Osvuran et al., 2022) obtained from Full Waveform Inversion and primarily based on data from Turkey to run Specfem3D forward simulations of the finite fault solutions for both events to check whether a well-resolved 3D model produces significant improvements to waveform fits compared with 1D-based simulations. In addition, we used the 3D velocity model to calculate Green's functions (GFs) for larger aftershocks (Mw≥5.0) and estimated moment tensors (MTs) using the Moment Tensor Uncertainty Quantification (MTUQ) code. We compared the MT solutions with results from 1D GFs to evaluate the 3D model performance in terms of improvements to waveform fitting characteristics and MT parameter resolution.

February 6, 2023 Kahramanmaraş Earthquake Sequence: Preliminary Observations Along the Surface Rupture and Slip Distribution of the Mw 7.5 Ekinözü Earthquake

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The 6 February 2023 Kahramanmaraş earthquake sequence started with a magnitude 7.8 (USGS) earthquake at 4:17 a.m. local time with epicentral coordinates of 37.288 N, 37.043 E. This earthquake was initiated along the Narli fault and propagated onto the tectonic boundary between the Anatolian and Arabian plates, rupturing it bilaterally for over 300 km. This earthquake was followed by a magnitude 7.5 (USGS) at 1:24 p.m. local time, with the epicenter near Ekinozu (38.089°N, 37.239°E). The Ekinözü earthquake also ruptured bilaterally and resulted in approximately 140 km of co-seismic surface rupture. Field investigations supplemented with interpretations of high-resolution sUAS (small unmanned aircraft systems) and helicopter images together with USGS-led interpretations of high-resolution optical imagery from WorldView 1-3satellites (© 2023 Maxar) show that the surface rupture occurred on two different left-lateral strike faults: The first, known as the Çardak fault, extends from the town of Göksun in the west to Bıçakçı village in the east. The second is the newly-named Çığlık Fault, a NE-SW-striking left-lateral fault that does not have a strong geological or a geomorphological imprint before this earthquake.

The surface trace of the Çardak Fault can be divided into two geometric sections: The arc-shaped western section extends between Göksun and Nurhak for nearly 80 km. Slip along the eastern half of this section was typically over 6 meters, reaching over 8 meters at the maximum slip location east of the epicenter. The second fault section extends nearly E-W between Nurhak and Bıçakçı for almost 20 km. The average of slip measurements along this linear section of the Çardak fault is around 2.5 m. Our field investigations indicate the rupture established a new trend after Bıçakçı instead of utilizing the E-W-oriented Sürgü Fault. The average slip along this new 40 km-long fault zone, here named Çığlık fault, is about 1m, with maximum left-lateral slip reaching ~2.5m.

Rapid Surface Rupture Mapping of the 6 February 2023 Kahramanmaraş Earthquake Sequence to Support Response Efforts

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The 6 February 2023 Kahramanmaraş earthquake sequence in southeastern Türkiye caused >500 km of surface rupture on the left-lateral East Anatolian and Çardak faults. Constraining the length and magnitude of surface displacement on the causative faults is critical for loss estimates, recovery efforts, and rapid identification of impacted infrastructure. To support these efforts, we rapidly mapped the surface rupture and released the results to the public (DOI: 10.5066/P985I7U2) on 10 February 2023 with subsequent updates. We interpreted the initial simplified rupture trace from sub-pixel offset fields derived from Sentinel-1 synthetic aperature radar image pairs acquired on 29 January and 10 February 2023 and supplemented and revised it as high-resolution (<0.7-m pixel) optical images from WorldView 1-3 satellites (© 2023 Maxar) became available. This mapping helped guide fieldwork and USGS finite fault modeling. It also constrained loss estimates, stress change calculations, and deformation models. The M_w7.8 earthquake on the East Anatolian fault created at least ~335-340 km of surface rupture on the primary fault, plus ~40-45 km on two fault splays. The M_w7.5 earthquake on the Çardak fault created up to ~175 km of surface rupture on the primary fault, plus possibly ~20 km on a north-south splay in the west. Field verification was critical for constraining surface rupture length and displacement of the Çardak fault because we lacked high-resolution imagery coverage for more than one month after the earthquake. The M_w7.8 earthquake is amongst the longest historic surface ruptures, but on-fault slip along it is moderate with a maximum of ~6-7 m. The M_w 7.5 earthquake has larger offsets, up to ~8-8.5 m, and both ruptures vary between localized and distributed deformation along strike. Additionally, comparing the mapped ruptures with crowd-sourced infrastructure maps enables identification of places where key infrastructure (e.g., roads, pipelines, railways, hospitals) could have been cut by the surface rupture. Such maps can assist first responders and field reconnaissance teams in directing response efforts.

3D Near-Field Surface Deformation, Stress and Friction of the 2023 Mw 7.8 and Mw 7.6 Kahramanmaras Earthquakes Measured by Alos-2, Sentinel-1 and Sentinel-2 Pixel Offsets

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The variation of stress on faults is important for our understanding of fault friction and the dynamics of earthquake ruptures. However, we still have little observational constraints on absolute stress magnitudes, or their variations in space and in time over the seismic cycle. Here, we use 3D surface deformation measurements in the near-field of the 2023 Mw 7.8 and Mw 7.6 Kahramanmaras earthquakes to estimate the distribution of 3D slip vectors along both ruptures and invert them for the stress state and frictional properties, using the approach of Milliner et al. (2022). To estimate the 3D coseismic surface deformation we invert azimuthal and range pixel offsets estimated from ascending and descending Sentinel-1 and descending ALOS-2 radar data. Radar were processed using ISCE, and pixel offsets from Sentinel-2 optical imagery estimated using the newly developed COSI-Corr+ software. The coseismic slip magnitude shows a marked decrease of ~3 m along a restraining bend of the Mw 7.8 mainshock rupture. We assume this reflects the quasi-static effect of a decrease in the initial shear stress due to the change of the fault geometry with respect to the ambient stress field. We use this to invert for the static and dynamic friction of the ruptured faults and the absolute stress magnitude and its orientation.

Field Evidence on Seismo-tectonic and Seismo-gravitational Structures Related with the February 2023 Earthquake Sequences in Türkiye

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Three devastating earthquakes; On February 6th, Pazarcık (Kahramanmaraş) Mw: 7.8, Elbistan (Kahramanmaraş) Mw: 7.6, and on February 20 th Defne (Hatay) Mw: 6.4 occurred in the southeastern and eastern parts of Türkiye. The first dual earthquakes contiguously occurred, only separated at 9 hours apart. The first earthquake was on the Türkoğlu-Pazarcık, Erkenek and Amanos segments, which are included in the Eastern Anatolian Fault Zone, and the second one occurred on the Çardak Fault, the western termination of the Sürgü Fault and southwestern part of the Doğanşehir Fault Zone together. The last earthquake occurred within the impact area of the Antakya Fault Zone. All three earthquakes also show minor oblique and major left-lateral strike-slip faulting characters. During the field observations, the earthquake-induced geological structures were evaluated under two main members. These are; (1) Seismo-tectonic (surface rupture-induced) and (2) Seismo-gravitational (seismic shaking/seismic wave-induced) structures. The structures were examined and evaluated by both field observations and numerical data obtained in cm precision by high resolution images with Unmanned Aerial Vehicles (UAV's)-mounted GNSS-RTK module shortly after the earthquakes. In addition, remote sensing methods such as radar interferometry, satellite images and aerial photographs were used during the studies. Combining all indicated data, the surface rupture of the first two major earthquakes, with a length of over 450 km, was mapped. This surface rupture is characterized by approximately reaching 7 meters left lateral, and in some places have 2 meters vertical components. Seismo-gravitational features have also been grouped under (1) Liquefaction structures (seismites) and (2) Slope movement structures such as translational and rotational landslides, rockslides, rockfalls, topples, debris flows and avalanches, lateral spreading's and some complex structures. One of the major earthquake-induced slope movement structure "we called Tepehan Rockslide", which was formed by the first earthquake, is located in the Altınözü district of Hatay province.

Non-Uniqueness Dilemma in the Kahramanmaras Tsunami Source Solutions at Different Frequencies: Hint for Excitation by Transient Rayleigh Waves From a Strike-Slip Rupture

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The 2023 Kahramanmaras earthquakes created a small tsunami in the northeastern Mediterranean Sea with amplitudes reaching ~30 cm near the Iskenderun Bay. Simulation of a large number of tsunami scenarios with tectonic and geomechanic sources designed using attenuation models reveal the possibility of a seismicall triggered submarine landslide matching the moderate domonant frequency observed in the records from local tide gauges. However a long-period, emerging precursor to the landslide tsunami signal in tide gauges records close to the Iskenderun Bay points to an 'indirect', near-field contribution of Rayleigh waves in shallow water as shown by numerical simulations. This observation is noteworthy, especially considering the surface deformation lobes pointing 'away' from the sea, in a region otherwise considered to be a "safe zone". This result, along with former observations in the case of recent tsunamis urges the re-evaluation of existing tsunami hazard assessments in coastal regions at or close to strike-slip faulting.

U.S. Geological Survey's Hazard and Impact Assessment of the 2023 Türkiye Earthquake Sequence

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The 2023 Türkiye earthquake sequence caused devastating losses throughout the region. The U.S. Geological Survey pursued rapid characterization of all aspects of the largest earthquakes, including their complex fault geometries, critical to estimating the shaking and impact. ShakeMap shaking constraints—and thus PAGER loss estimates—naturally evolved with time as we obtained more stations, macroseismic intensities, and better resolution of the fault rupture complexity. Complicating single-event impact assessments was the substantial contribution of aftershocks to losses. This led to reexamining Composite ShakeMap—depicting the maximum shaking at each location for the entire sequence—to estimate the total losses better. Though this approach does not accommodate complexities of population migration (displaced, sheltered, or relocated persons), weakened structures, or reduced building exposure due to prior collapses, loss estimates are improved by considering the maximum shaking integrated across the sequence. Composite ShakeMap also depicts the shaking history at each location, allowing modelers to estimate the number of times a structure's design level was exceeded. We also introduce a new framework for more rapidly ascertaining the fault dimensions necessary for accurate shaking estimates. Our proposed framework involves enhanced multidisciplinary, near-real-time collaboration among seismologists, engineers, geologists, and geodesists—harmonizing disparate seismological, faulting, imagery, and impact observations needed to constrain rupture complexity controlling the shaking distribution. Lastly, we report on detailed building damage and ground failure estimates, combining prior models and updated with satellite imagery. Such rapid updating is part of an evolving USGS strategy to improve our impact assessments with ground-truth observations rapidly.

Geotechnical Characteristics of Golbasi (Adiyaman) Soils Exhibiting Large Deformations on February 06, 2023 Earthquakes

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On February 6, 2023, M_w=7.7 and M_w=7.6 earthquakes struck the southeast Turkiye region including eleven municipal areas and several districts at 04:17 and 13:24 local time. One week after the earthquake, a geotechnical earthquake engineering team from Dokuz Eylul University conducted a field investigation for building damage assessment and soil site effects in Golbasi, Adiyaman. Our team carried out a reconnaissance study for damaged structures and ground conditions to evaluate the soil behavior during and after the earthquakes. Reconnaissance studies and data gathering in local engineering and constructions firms revealed that extensive damage was related to softening of cohesive soils rather than liquefaction in the lake side zone of Golbasi. Bearing capacity loss of the building foundations were in either excessive uniform settlement or rigid tilt modes for recently constructed reinforced concrete building with mat foundations. Buildings that were built before 2000, however, severely damaged as a result of poor foundation systems and often caused life losses. Observations made with 10 to 15 days intervals in the area and personal discussions with locals who experienced the earthquakes in person showed that the sink and tilt response of the buildings are time dependent obeying to the cohesive nature of the soil profile. Geotechnical properties of the site soils including soil profiles, grain size distribution, consistency limits,

water content, SPT blow counts, V_{s30} and V_{s100} that were acquired in site investigation study are presented in this proceeding. Comparisons with pre-earthquake site investigation data acquired from archives are made where available.

Near-Fault Ground Motion Modeling Due to the 2023 M7.8 Kahramanmaras Earthquake and Impacts on Local Buildings

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The M7.8 earthquake that occurred on 02/06/2023 had catastrophic effects on cities near the East Anatolia fault (EAF). The maximum PGA measured at the strong motion station TK.2708 reached 1.8g, almost three times the PGA predicted by the regional ground motion model. Several strong motion stations near the EAF with epicenter distance as far as 150 km to the southwest of the earthquake epicenter actually measured huge peak ground acceleration (PGA) larger than 1g. The spectrogram analysis of the near-fault strong motion data shows the directivity effects of the rupture, that explained the surprisingly high near-fault PGA far from the earthquake epicenter. In addition to the rupture effects, the soil layer in Hatay can amplify the ground motion 2-5 times according to previous site effect studies in this region. Using the synthetic acceleration from the dynamic rupture modeling with the consideration of the site effects, we analyzed the impacts of the M7.8 earthquake on local buildings in cities near the EAF. The collapse of typical mid-rise buildings in Kahramanmaras and Hatay was modeled by the Bullet Constraints Builder (BCB), and visualized with the Blender engine.

Dynamic Site Response Analysis of Adiyaman Golbasi Soils During February 06, 2023 Kahramanmaras Earthquakes

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The severity of devastating effects caused by strong earthquakes in sites is largely determined by factors such as site amplification, liquefaction, and soil softening. It is crucial to consider the significant impacts of site conditions when conducting site response analyses, as they play a critical role in designing structures. The primary objective of this investigation is to explore the ground response during two severe earthquakes with moment magnitudes of M_w=7.7 and M_w=7.6, respectively, which occurred in Golbasi district of Adiyaman province. To accomplish this goal, a one-dimensional nonlinear dynamic site response analysis was performed. The analysis is intended to investigate the behavior of the soil during seismic events and provide insights into the zonal response of the soil. Dynamic soil parameters were obtained through site investigations conducted in the earthquake region, as well as through laboratory and field tests, including Standard Penetration Test (SPT) and micro-tremor analyses. A dynamic nonlinear site response analysis was carried out on the pertinent soil profile by implementing the two-directional components of the acceleration-time records that were obtained from the seismic recording station located in the area where the earthquake with a moment magnitude of M_w=7.7 occurred. The region was then re-modeled for the M_w=7.6 earthquake by taking into account pore water accumulation and stiffness softening following the first earthquake. Analyses were repeated using the components of the second large earthquake allowing for more accurate modeling of the successive impact of two major earthquakes on the soil profile. Achieved results showed that two-stage site response analysis was capable of capturing extensive softening of low plastic cohesive soils.

Months-Long Preparation of the 2023 Mw 7.8 Kahramanmaraş Earthquake, Türkiye

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Short term prediction of the magnitude, time, and location of earthquakes is currently not possible. In some cases, however, behaviour has been documented that has been retrospectively considered as precursory. Some models hold that on a timescale of several years, increasing levels of background seismic activity may signify enhanced damage generation affecting a broader area. Localization of seismicity and/or aseismic deformation in these models leads to spatial coalescence, stress transfer and non-local interaction of foreshocks, and a nonlinear increase in seismic activity. Perhaps due to the structural complexity of fault zones, however, proposed seismic and aseismic preparatory deformation processes, when present, are strongly variable and still not well understood. Here we present evidence for an extended earthquake preparation process starting in June 2022 and lasting approx. 8 months prior to the occurrence of the February 6th, 2023, M_W 7.8 Kahramanmaraş earthquake on the East Anatolian Fault Zone. The apparently precursory activity ahead of the earthquake is composed of a handful of isolated spatio-temporal clusters within 65 km of the future earthquake epicentre. Some of these clusters display accelerating seismic activity starting ca. 8 months before the mainshock, non-Poissonian inter-event time statistics and distribution of magnitudes in time, as well as low Gutenberg-Richter *b*-values. Close to the mainshock epicentre and during the weeks prior to its rupture, seismic quiescence is observed. Our observations suggest a different initiation mechanism compared to the cascade of close (<200 m) foreshocks observed before the M_W 7.6 Izmit 1999 earthquake. The trends of seismic preparatory attributes for this earthquake follow those previously documented in both laboratory stick-slip tests and numerical models of heterogeneous earthquake rupture affecting multiple fault segments. With more comprehensive and effective earthquake monitoring, it may be possible to recognize a preparation phase before at least some significant earthquakes.

Landslides Triggered by the February 6, 2023 Kahramanmaraş Earthquake Sequence

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The devastating Kahramanmaraş earthquake sequence occurred on February 6, 2023. Two main events, estimated as Mw 7.7 and Mw 7.6 by the Kandilli Observatory and Research Institute, occurred nine hours apart and affected 10 cities and subjected an area >100,000 km2 to shaking levels known to trigger landslides (PGA >8% g). About 15% of this area has slopes greater than 20°. Initial estimates of globally available predictive landslide models indicated an extensive spatial distribution of hazard and population exposure, and many road blockages. In the days immediately following the earthquake, we examined high-resolution satellite images and aerial photos and used other remote sensing techniques (e.g., InSAR, change detection) to search for landslides of particular concern for human safety and to provide situational awareness to authorities. We also sought to gain better insight into the co-seismic landslides and their possible post-seismic consequences. This remote campaign was supplemented a few weeks after the earthquake by field surveys. Here we present the preliminary findings of these investigations.

Our observations showed that the earthquake sequence resulted in numerous co-seismic landslides, especially in the north. Surface rupture through mountainous terrain caused some large and sometimes fatal landslides. Rock falls were the most widely observed co-seismic landslide type though we also noted bedrock rotational, planar slides, lateral spreading, and rock avalanches. Lithology, spatial variability of ground shaking, topographic relief, and the arid/semi-arid climatic conditions appear to be the main variables controlling the spatial distribution of the observed co-seismic landslides. Intense ground shaking strongly deformed and damaged many hillslopes and mobilized some deep-seated landslides, so in the post-seismic period, we expect that heavy rain and snowmelt may result in a considerable number of additional failures and deformation on those hillslopes. Therefore, long-term monitoring may be needed to understand the earthquake legacy effect and post-seismic hillslope response.

Causes of the Earthquake Damage of Buildings in the Aftermath of the February 6, 2023 Earthquake

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A devastating earthquake centered Kahramanmaras hit 11 cities of TURKEY on February 6, 2023 and caused significant damage to buildings and infrastructures. The purpose of this study is to analyze the damage reason of the existing buildings within the affected areas. The damage was measured from minor to total collapse and has to be evaluated in order to be ready for the upcoming earthquakes.

As is known, earthquakes are big laboratory's and clearly reveal the inadequacies in structures. As a result of the observations carried out after the earthquake's, it may be possible to make changes to the code regulations. In this context, it is decided to examine the damage reasons of building in 11 cities exposed to the earthquake in detail. Initially, the numbers of buildings with minor damage, moderate damage, severe damage and completely displaced in these cities were attained. By these information, It will be possible to examine the demolition rate and damage reason of the buildings constructed with the old regulation and with the other regulations.

After determining the damaged reasons, it will be possible to determine the main deficiency that caused demolition for the structures' that were built by all known code regulations. Afterwards, it is planned to set out the measures to be taken to hinder total collapse and to suggest new proposals for code regulation to build a truly earthquake-resistant structure. Thus, it will be possible to be prepared for earthquakes that may occur in the near future.

Artificial Neural Networking and Statistical Analysis of Turkey's Earthquake 2023

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The purpose of this study is to provide a statistical analysis of earthquakes that have occurred on the Anatolian Tectonic Plate in Turkey and Syria (Latitude: 34.124 to 43.44 and Longitude: 41.549 to 33.064). This study took into account the Mw 7.8 and Mw 7.5 earthquakes that occurred on February 6, 2023, in Turkey. An analysis of previous earthquake data from 1 January 1960 to 1 February 2023 has been conducted. Through 11 March 2023, aftershock data have also been examined. With the Gutenberg-Richter law and the Maximum Likelihood Estimator, the complete dataset's a- and b-values have been estimated, and the seismicity of the area has been determined. To perform all statistical analysis and visualization, as well as to clean and filter data, Python programming has been used. Zone maps are plotted using the tableau. Additionally, we calculate the mean, median, standard deviation, and coefficient of variation to support upcoming analytical work.

In the paper, artificial neural networks are also discussed as machine learning algorithms for magnitude forecasting. The mathematically calculated parameters that are used as the input layer of the neural network model are Longitude, Latitude, Energy E, Energy J, and Stress Drop. The goal of the study is to develop a neural network model that can accurately predict earthquake data across the board.

Near-Real-Time Estimates of Fatalities Due to the M7.8 Earthquake on 6 February 2023 in Turkey

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We issued a QLARM red alert of 3,000 to 6,000 fatalities 30 minutes after the large earthquake on 6 February 2023 on the East Anatolian fault. This estimate was based on a point source model of an estimate of M7.6, considering that it might be only an M7.4, as a different report suggested, and that the depth of the greatest energy release may have been deeper than 10 km. This alert contained the warning that the point source model used was a poor approximation. The following aftershocks suggested a complex pattern that did not allow the construction of a line source model during the first minutes after the earthquake. A month after this quake, ground observations, aftershocks, satellite images and moment tensors showed that the rupture was about 300 km long and could be approximated by a line source of two straight segments and that the depth could be modeled as 18 km. We used the following coordinates to define the two segments of the line source from the SW to a middle point and farther on to the NE end: 36.17E/36.14N, 36.95E/37.44N, 38.48E/38.11N. With assumed average local transmission of seismic energy and average soil conditions beneath buildings, and assumed main energy release at a depth of 18 km and M7.8, the number of fatalities are estimated as 76,000 to 115,00 for the M7.8 earthquake alone. At the time of this writing, the total fatality count of all earthquakes in the February 2023 sequence is at the time of this writing 54,000 and climbing. The purpose of our fatality estimates in near-real-time is to help first responders worldwide to decide whether or not to mobilize for helping to save injured. Although the fatality range issued within 30 minutes after the earthquake was an underestimate, the alert level was "red", the highest urgency we can assign, sufficient to urge first responders to rush immediately to the scene.

Science Communication During an Actively Unfolding Disaster

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The communication of science in the minutes, hours and days after a major earthquake disaster is an important part of emergency mangement and public safety. The earthquakes that affected Türkiye and Syria in February 2023 brought this into focus. There was an massive demand from the public and the media for information to better understand what was happening.

People in the affected region and around the world want to understand how and why things are happening during crisis situations, so communicating the facts around the science of earthquakes is important. Additionally, we need to understand what is the relevant science that needs to be communicated, and be aware of the tone and framing that we use to deliver that information, and how it could be interpreted.

In this talk, I will give an overview of the communication successes and pitfalls surrounding the earthquakes in Türkiye, discuss why empathy is important during crisis communication, and outline some lessons learned from these events.

February 2023 Mw 7.8 Earthquake Sequence in Turkey [Poster]

Poster Session • Wednesday 19 April

Conveners: Xyoli Pérez-Campos, xyoli@igeofisica.unam.mx, Universidad Nacional Autónoma de México and Elizabeth Vanacore, elizabeth.vanacore@upr.edu, University of Puerto Rico, Mayagüez

Characterization of Source, Path and Site Effects on Ground Motions From the 2023 Kahramanmaraş, Türkiye, Earthquake Sequence

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We seek to understand the physical processes that generated the strong ground motions observed during the 2023 Kahramanmaraş, Türkiye, earthquake sequence, reasons why recorded motions may differ from existing ground motion models (GMMs), and factors controlling the observed variability. The devastating 2023 Türkiye earthquake sequence, which included the M7.7 Pazarcik mainshock and the M7.5 Elbistan aftershock, occurred along the Eastern Anatolian Fault Zone. Because these destructive earthquakes represent a nearly unprecedented set of near-source ground-motion records, understanding their genesis could improve GMMs and hazard estimates in Türkiye and worldwide. We perform an ensemble GMM residual analysis, examining ground motions from the 2023 sequence as well as other previous regional earthquakes, using a total of 63 M5+ events, including the 2010 M6.1 Elazig and 2020 M6.7 events, recorded on 1116 stations. Using many smaller earthquakes allows for robust sampling of source, site, and path effects, including consideration of more complex spatially varying and azimuth-dependent effects that we might expect to be present on a nationwide scale. We consider ground-motion residuals for spectral acceleration between 0.05s and 10s, as well as peak ground motions relative to a reference GMM of Boore et al. (2014; BSSA14) and partition them into components representing repeatable source, path, and site effects to understand the relative contribution of each. The BSSA14 GMM includes an anelastic attenuation term that is specific to Türkiye, and we observe that overall, the ground motions for the two largest events are well modeled at all distances and periods. Directivity is evident in the ground motions for the largest events, consistent with the complex multi-fault rupture. For the moderate aftershocks, the data within ~50km are well modeled by BSSA14 but show overprediction at distance, implying anelastic attenuation for the smaller events on the Eastern Anatolian Fault Zone is stronger than along the Northern Anatolian Fault Zone, from which data was used to constrain the model.

Coastal Effects of the Kahramanras Turkey-Syria Twin Earthquakes of February 6th, 2023: Recommendations for Using Geospatial Analysis Tools to Predict Abnormal Water Impact

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On February 6th, 2023 (at 01:17:36.1 UTC) a strong M7.8 earthquake with epicentral location 37.17 N and 37.08 E happened approximately 30 km WNW of Gaziantep city, in Southeastern Turkey (CSEM/EMSC), and about twice the distance from the border with Syria. This earthquake was followed by a similar magnitude earthquake (M7.5) approximately nine hours later on the same day (at 10:24:49 UTC) with epicentral location 38.11 N 37.24 E near Elbistan, Turkey, about 100km north of the first event. Several aftershocks have ensued with the largest being a M6.3. Both earthquakes caused extensive damage and fatalities (>> 45,000 in Turkey and Syria) through ground shaking and secondary effects. The M7+ earthquakes were widely felt in Turkey and surrounding areas. Felt reports from both events were submitted to EMSC for this event in Greece, the Balkans and Italy in distances exceeding 1200 km. Flooding was also reported in few locations such as in Alexandretta (Iskenderun) and in Salqin, Idlib, Syria. Sea Level stations recorded a small tsunami and tsunami runup was observed in at least 5 locations in Cyprus and Turkey along with seiching in Gaziantep.

Seismic seiching is used often to describe the surface oscillations generated in enclosed or semi-enclosed water basins due to earthquake ground motions. Such oscillations have previously been associated with distant, regional and local earthquakes while it has been suggested through seismic and spatial analysis that they are associated with the presence of thick (>1 km thick) unconsolidated sediments (Barberopoulou et al. 2004, 2006 & 2008; McGarr, 1968). Only a handful of earthquakes have relatively good data to understand the occurrence of standing waves due to seismic motions. In this work, we outline a geospatial model with the major input parameters we believe are attributing to the presence of standing waves associated with an earthquake. We aim for using GIS tools to help in predicting the locations of unusual wave activity which may also be associated with the potential of soil liquefaction occurrence.

Dynamic Rupture Models for the 2023 M7.8 Turkey Earthquake Along the East Anatolian Fault Zone

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On February 6th, 2023 Southern Turkey and Northern Syria were hit by two devastating earthquakes. The first earthquake, a M 7.8 event, ruptured the main East Anatolian Fault (EAF) zone and the second earthquake, a M 7.6 event, ruptured the Sürgü Fault. In this work we focus our attention towards the first earthquake and use 3D dynamic rupture simulations to try and highlight some of the physics behind the rupture propagation. The M7.8 event is believed to have nucleated on a branch fault southeast of the main East Anatolian Fault zone which was able to propagate from the branch onto the EAF causing a much larger event rupturing over 300 km. There are many unanswered questions regarding the rupture process of this event. Firstly, what conditions allowed for rupture on the branch to propagate onto the main fault? Secondly, how was the rupture able to propagate bilaterally on the EAF? Shouldn't part of it be stress shadowed from slip on the branch? How do the geometric complexities along the EAF influence how the rupture propagated? In an attempt to answer some of these questions we construct a 3D finite element mesh of the ruptured area for the M7.8 event and in this study we do not include the Sürgü Fault which hosted the subsequent M7.6 event. We embed all the faults in a large elastic medium and we force nucleation to occur on the branch segment. Initial results seem to indicate that both a substantial stress drop on the branch fault, and a high stressed intersection can allow for the rupture to propagate onto the EAF. This work is still preliminary and we intend to further highlight aspects of the rupture in future models, using available data such as GPS and InSar to help put constraints on our models.

Establishment and Success of the AFAD Earthquake Clearinghouse and Reconnaissance Data Collection Efforts Following the Mw 7.7 and Mw 7.6 Kahramanmaras Earthquakes in Eastern Turkey

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The devastating Mw7.7 and Mw7.6 earthquakes that struck eastern Turkey on February 6, 2023, prompted the establishment of an earthquake clearinghouse at AFAD (The Disaster and Emergency Management Presidency of Turkey) in Ankara within a week. To coordinate the TUBITAK-funded reconnaissance teams of approximately 577 researchers from 61 universities across Turkey, AFAD and TUBITAK teams worked together under the earthquake clearinghouse located in Ankara. EERI (Earthquake Engineering Research Institute) also offered its tools and forms, including the EERI's mobile application and EERI field forms, to support the reconnaissance performances. After reviewing both EERI's mobile application and ESRI (Environmental System Research Institute)-ArcGIS Enterprise (Survey123, Dashboard, WorkForce, etc.), the decision was made to use ArcGIS Enterprise due to its adaptability and support by ESRI-Turkiye and its team.

The reconnaissance data collected from the field, including information on liquefaction, landslides, surface rupture, and building damage, was immediately archived, transferred to the AFAD server, and sent to national agencies and ministries of Turkey for fast recovery plans and site selection of new settlements in the disaster area. This first earthquake clearinghouse established after the Kahramanmaras earthquakes was a big success, even without prior exercise. The physical earthquake clearinghouse also functioned as a hub for EERI from the US and other teams from Europe and Asia. The AFAD Earthquake Clearinghouse will continue to play its role in bringing stakeholders together around the archived data for further investigations and research, and in encouraging national and international collaboration for better earthquake mitigation and action plans, thus making us better prepared for future major earthquakes.

Flow Type Deformations of Onshore Soils in Adiyaman-Golbasi During February 06, 2023 Kahramanmaras Earthquakes

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On February 06, 2023 two consecutive earthquakes took place in Kahramanmaras Province causing extensive ground surface deformations in Golbasi, Adiyaman. Golbasi is located on the south and north bank of Golbasi Lake, a pull-apart tectonic depression basin. Flow type deformations occasionally observed along the coastline of Golbasi took attention of researchers following the earthquake. Although there is evidence of flows on the north bank, the most spectacular example was seen on the south coast of the lake. A large portion of an recreational area including buildings sank into the water posing flow type deformations. Since the mechanism (sliding of softened cohesive or liquefaction of sandy soils) causing such large deformations has not yet been understood yet, a preliminary site investigation study including acquisition of images using unmanned aerial vehicles, microtremor measurements to obtain V_{s30} and V_{s100} profile and boreholes was realized. Preliminary results involve elevation map of the study area after the earthquake, 2D and 3D illustrations of the site and the soil profile. The study concludes with two dimensional slope stability analyses.

Investigation of Damages in Schools and Buildings in Adıyaman Gölbaşı After February 6, 2023 Earthquake

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The earthquakes that occurred on the Eastern Anatolian Fault on February 6, 2023, caused a great structural destruction in the region. Many buildings in different cities were destroyed or severely damaged. One of the regions where it suffered the most intense damage is Gölbaşı district in Adıyaman province. Widespread liquefaction has occurred on the ground of the area where the city is located. Due to the soil liquefaction in question, uniform and non-uniform large settlements have occurred in many buildings, and the buildings have received extensive damage due to these settlements. When the school buildings in the city, especially the school buildings, are examined in the region, it is observed that the settlement due to liquefaction in the school buildings is less than the other buildings and the structural damage is limited.

In this study, the causes of the structural damages that have occurred in the buildings in the Gölbaşı district of Adıyaman and especially why the school buildings are less damaged than other buildings will be examined. For this purpose, the structural features of the schools will be explained in general, the differences in design criteria compared to other buildings will be examined and evaluations will be made about why the structural damage in the school buildings is limited. As a result of the study, suggestions will be made for future changes regarding the design criteria in the current earthquake regulations.

Performance Evaluation and Updates to a Geospatial Liquefaction Model Using Observational Data From the February 2023 Earthquake Sequence in Turkey and Syria

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Geospatial ground failure models are routinely implemented as part of the Ground Failure tab of the USGS Event page. After the February 2023 Earthquake sequence in Turkey, ground failure maps were disseminated for the Mw7.8 and Mw7.5 events. In addition to the Zhu et al. (2015) and Zhu et al. (2017) models, the authors have an updated geospatial liquefaction model for the region (Zhan et al., 2023) and have developed an estimate of model uncertainty for the Zhu et al. (2017) model. Reconnaissance reports from the earthquake sequence have identified numerous observations of liquefaction with many observations in the port city of Iskenderun and in Gölbaşı, especially along Gölbaşı Lake. In addition to field liquefaction observations, we will analyze pre and post SAR image pairs and interferometric phase information to determine whether liquefaction deformations can be detected. In this poster, we will present the geospatial liquefaction model predictions from the three models with georeferenced observations. We will evaluate performance of the three models and provide recommendations on regional specific updates. Geospatial liquefaction models can be divided into liquefaction susceptibility and event specific components. Using Bayesian sequential learning, we will demonstrate a regional model updating method that can be used to improve performance of geospatial liquefaction models by updating the susceptibility component of the model for that region.

Preliminary Analysis and Model of the Complex Rupture Dynamics Behind the Mw 7.8 and Mw 7.5 Kahramanmaraş Earthquakes in Turkiye

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The Kahramanmaraş seismic sequence has involved several segments of the East Anatolian fault system in Turkiye with two $M_w > 7$ earthquakes and widespread aftershock activity. Its spatial and temporal evolution showcases strong interactions among different fault patches. We characterize such complexity by focusing on the dynamics of 6th February 2023 M_w 7.8 Nurdagi mainshock (occurred at 4:17 am local time) and the M_w 7.5 Elbistan event, which followed about nine hours later, and their relationship with early aftershock activity. We show that the first event, after breaking a lateral fault with low rupture velocity, triggered a cascading instability on the main fault with at least two dynamic transfers from one patch to another, producing bilateral rupture with high rupture velocity. Sub-events are detected and relocated by analysing the frequency content and arrival times of accelerometric seismograms recorded by the AFAD and KOERI stations. We model the expected variations of rupture velocity based on the rheological variability of rock volumes and local stress drop during faulting. Rupture velocity turns out to be positively correlated with shear strength and negatively related to local stress drop and early aftershock rate. Our results provide a qualitative explanation of the observed complex dynamics of the main event and following seismic activity. We also notice that the same framework can be applied to cascade ruptures to explain why large strike-slip faulting events are featured by a significantly higher probability of fast rupture velocity, even super-shear as it occurred with the second M_w 7.5 mainshock, than in contractional and extensional faulting styles. Our findings also suggest a role for almost instantaneous event triggering in enhancing ongoing ruptures, producing substantial limitation for the prediction horizon of seismic events.

Rapid Characterization of the 2023 Kahramanmaraş, Türkiye, Earthquake Sequence at the USGS National Earthquake Information Center

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The February 6, 2023, M_w7.8 Pazarcık and subsequent M_w7.5 Elbistan earthquakes generated strong ground shaking that resulted in catastrophic human and economic loss across south-central Türkiye and northwest Syria. The rapid characterization of the earthquakes, including their location, size, fault geometries, and slip kinematics is critical to estimate the impact of significant seismic events. The U.S. Geological Survey National Earthquake Information Center (NEIC) provides real-time monitoring of earthquakes globally. Rapid source characterization products (i.e., location, magnitude, mechanism, and finite-fault model) are used as input to NEIC's ground motion estimation product, ShakeMap, and in turn, the loss estimation product, PAGER. We describe the seismic characterization products generated and made publicly available by the NEIC over the two weeks following the start of the earthquake sequence in southeast Türkiye, their evolution, and how they inform our understanding of regional seismotectonics and hazards.

The kinematics of rupture for the two earthquakes was complex, each involving multiple fault segments. Optical and radar satellite imagery were critical for identification of the surface rupture and defining the orientation of fault segments for slip characterization. In the days following the earthquakes, NEIC also acquired dense local seismic and geodetic datasets that facilitated robust source characterization and impact assessment. We discuss how we may improve the timeliness of NEIC products for rapid assessment of future seismic hazards, particularly in the case of complex ruptures.

Reconnaissance Geological Observations of the February 06, 2023 Kahramanmaraş, Türkiye Earthquakes

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The Kahramanmaraş, Türkiye earthquake sequence occurred on February 6, 2023 along the East Anatolian fault (EAF) system, resulting in widespread damage and casualties. The epicenter of the first event (Mw7.8) was approximately 35 km northwest of the city of Gaziantep along the Narlı fault and generated surface fault rupture of over 300 km along the EAF between Antakya and Karaköse. The second event (Mw7.5) located northwest of the EAF and initiated near the city of Elbistan, rupturing ~142 km of the Çardak-Sürgü faults. Subsequent to the earthquakes, the Geotechnical Extreme Events Reconnaissance (GEER) Association mobilized teams to the affected area to document perishable geological and geotechnical data. The investigation included a regional assessment of the impacts to infrastructure (i.e. bridges, pipelines) as well as documentation of the geological effects (surface fault rupture, liquefaction, lateral spread, landslides). Here we present surface slip measurements collected between the towns of İslahiye and Nurdağı, and near Narlı, Çiğli, Kartal, and Balkar along the Mw7.8 rupture and between the vicinities of Çiftlikkale and Barış along the Mw7.5 rupture. Left-lateral surface displacements along the Mw 7.8 EAF rupture were remarkably consistent, 3 to 4 m, but diminished to the south near Antakya to around 0.5 m. The Mw 7.5 event produced the largest recorded surface displacements of consistent 7 to 8 m left-lateral offsets. Along both ruptures, the surface trace followed tectonic geomorphic features that would have been recognized in pre-rupture mapping such as linear swales, saddles, and side-hill benches. However, in other areas the ruptures are expressed by breaks across the tops of shutter ridges, through bedrock knobs, and complex arrays of en echelon pressure ridges. Our efforts provide field validation of slip estimates determined by other methods (i.e. radar image analysis) and contribute to the overall assessment of the surface slip distribution. Additionally, the mapping observations highlight challenges in assessing surface fault rupture hazards.

Rupture Process of the February 2023 Mw 7.8 Earthquake Sequence in South-Central Türkiye and Northwestern Syria From Teleseismic P-Wave Data

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On February 6, 2023, two destructive earthquakes of Mw 7.8 and 7.6 struck the south-central part of Türkiye. The first event (E1) started on an off-fault branch near the East Anatolian Fault (EAF) and the second one (E2) occurred on the east-west trending Sürgü fault ~9 hours later. We use back-projection (BP) and finite fault inversion (FFI) with teleseismic P-wave to image the rupture process of these two earthquakes. For the BP, we use Alaskan stations and only target high cross-correlation coefficients (>0.6). The FFI uses 18 and 17 seismic recordings for E1 and E2, respectively, ensuring good azimuth coverage. We define segmented rupture-plane geometries using fault traces derived from satellite radar image pixel offset tracking. We parameterize E1 with 4 fault segments, each with a uniform dip of 89º, whereas E2 comprises 3 segments dipping 78º to the north. All segments are discretized into 5 x 5 km^2 subfaults, on which we solve for slip, rupture onset time, and rise time. In addition, we explore the model space using Bayesian inference to account for the non-uniqueness of the inversion solution.

Both the BP and FFI results indicate bilateral rupture propagation for both earthquakes. The BP results for E1 show that the rupture propagated to the northeast along a fault branch until it reached the EAF, then it continued along EAF to the northeast for up to ~55 s. The rupture to the southwest along the EAF, towards the Hatay province, appears to have been delayed and then terminated at ~80 s. For E2, we observe frequency-dependent BP results due to the directivity effect. The BP captures the rupture to the east and then northeast in a lower frequency range (0.1-0.5 Hz), while it images opposite rupture direction to the west in a higher frequency range (0.5-1 Hz). The FFI result of E1 shows at least three high-slip patches with the maximum slip of up to 8 m. The slip model of E2 shows high slip of above 8 m near the surface of the Sürgü fault, but less slip to the northeast and southwest. Overall, our modeled moment magnitudes of the two events are Mw 7.97 and Mw 7.77, respectively.

Seismic Activity and Aftershock Potential of the 6 February 2023 Mw 7.7 and Mw 7.6 Kahramanmaras Earthquake Sequence in Eastern Turkey

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The 2023 Kahramanmaras earthquake sequence in eastern Turkey began on February 6 and ruptured with a length of approximately 500 km in the deformation area of the Eastern Anatolian Fault Zone. The earthquake sequence started with a NE-SW oriented left-lateral shear and gained momentum about 9 hours later with another rupture in the E-W direction before continuing southwards. This type of rupture is similar to the pattern observed during the 17 August 1999 Kocaeli earthquakes and is formed by a strike-slip mechanism. The current seismicity in the deformation area has been highly active with small-to-moderate-sized aftershocks. A time-series analysis of the first 42 days of aftershocks (as of 20 March 2023 at 01:17:26 UTC) reveals that the high seismic activity observed in the first 21 days continued in the following days, with a significant decrease in the level of activity. However, the daily change in the new level is stable, indicating a high seismic energy potential still present in the region. The decreasing slope of the function characterizing the aftershock activity is low, indicating that the aftershock sequence is estimated to last for about 4.5 years using the completeness plane technique, recently proposed by the presenting author. The values of the parameters of the Modified Omori's formula used for the estimation of the aftershock sequence potential, K, c, and p, are controversial due to the short time period considered. The aftershock data used in the analysis were downloaded from the Kandilli Observatory and Earthquake Research Institute, Boğaziçi University electronic earthquake catalog. We present an analysis of the seismic activity and aftershock potential of the 2023 Kahramanmaras earthquake sequence in eastern Turkey. The results suggest that the region still has a high seismic energy potential, and aftershock activity may persist for years to come. This study can contribute to the development of strategies to mitigate earthquake damage and loss.

Sequence-Specific Updating of European ETAS Model: Application to the 2023 Türkiye-Syria Earthquake Sequence

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We analyse the spatio-temporal evolution of the aftershock sequence to the 2023 M7.8 Türkiye-Syria earthquake. We have recently calibrated a generic ETAS-based operational forecasting model for Europe, using a unified catalog and based on data between 1990 and 2015. Focusing on the earthquake sequence that started in February 2023 in Türkiye, we analyse how our model would have forecasted the temporal and spatial evolution of the sequence. We observed that the generic model clearly underforecasts the productivity of the sequence, and conclude that sequence-specific updating is required to achieve an acceptable fit between model and observations.

Here, we investigate the best way to visualize the results of aftershock forecasting and operational earthquake forecasting, and propose a new strategy for sequence-specific updating of model parameters to accurately describe the productivity and the spatial aftershock distribution, while leveraging on the parameters obtained from larger amounts of data within the European model. Our approach strives to avoid biases in the description of the temporal decay due to relying on short-term data. This is done by keeping certain model parameters fixed to the values inverted with our baseline model and calibrating the remaining parameters, using data of the ongoing sequence.

We assess the model's consistency with observations by comparing the forecasts issued by the basic and modified models to the observed events. Preliminary results suggest that keeping the temporal kernel and the productivity parameter a fixed provides better forecasts than the baseline model, already when small amounts of data from the sequence are available. Having identified a promising strategy for sequence-specific model updating, we plan to test it systematicall on a large number of earthquake sequences.

Moreover, propose prototypes of communication products that should support professional, societal stakeholders (e.g., decision makers, first responders) to take informed decisions, for example during rescue investigations.

Source, Path, and Site Effects on the Peak Velocity From the 2023 Pazarcik, Turkey Mainshock

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The peak ground velocities (PGV) from the Feb 2023 Pazarcik, Turkey earthquake mainshock were above average with a mean residual of 0.5 natural log units (factor of 1.65) for sites within 30 km of the rupture compared to the Abrahamson et al. (2014) ground motion model (GMM). Large PGV can be caused by several factors: forward directivity, fling, close distance to an asperity, path effects due to the 3-D crustal structure, and site effects. To determine the relative contribution of these effects to the large PGV values, we first baseline corrected the mainshock recording to recover the static displacement and remove the fling effects from the velocity time series. We then used the ground motions from M4-M5 aftershocks to estimate the site terms and non-ergodic path terms for a preliminary non-ergodic GMM using the iterative variable coefficient model (VCM) approach method of Sung et al. (2023). Morving the site and path terms removes some of the complexity from the distribution of the PGV. Finally, we compared the mainshock PGV residuals relative to the non-ergodic GMM to determine the correlation with the directivity model parameters of Bayless et al. (2021) and with the distance to the nearest asperity.

Sub- and Super-Shear Ruptures During the February 6, 2023 Mw 7.8 and Mw 7.6 Earthquake Doublet in Se Türkiye From Joint Inversion of Seismic and Geodetic Data

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An earthquake doublet (Mw 7.8 and Mw 7.6) with left-lateral strike-slip kinematics occurred on the East Anatolian Fault Zone (EAFZ) on February 6th, 2023. The events produced significant ground motions and caused major impacts to life and infrastructure throughout SE Türkiye and NW Syria. Here we show the results of earthquake relocations of the first 11 days of aftershocks and rupture models for both events inferred from the kinematic inversion of HR-GNSS and strong ground motion data considering a multi-fault, 3D geometry. We find that the first event nucleated on a previously unmapped NE-SW striking Nurdağı-Pazarcık fault before transitioning to the East Anatolian Fault (EAF) and rupturing bilaterally or ~ 350 km and that the second event ruptured the Sürgü-Çardak fault for ~ 160 km. Maximum rupture speeds are estimated to be 3.2 km/s for the Mw 7.8 earthquake. For the Mw 7.6 earthquake, we find super-shear rupture speed of 4.8 km/s for the westward rupture propagation but sub-shear speed for the eastward rupture propagation at 2.8 km/s. Peak slip for both events is estimated to have been as large as ~8 m and ~6 m, respectively. We will also show early results for static and dynamic stress-change modeling and discuss the potential triggering mechanisms between the first and second e in the doublet.

The Operational Service of Aristotle-Eenhsp for the February 6, 2023 Earthquakes in Turkey-Syria

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The ARISTOTLE-eENHSP is a service funded by DG ECHO (Humanitarian Aid and Civil Protection) of the European Union that provides the European Union Emergency Response Coordination Centre (ERCC) with a multi-hazard expert assessment for emergencies triggered by natural hazards. Its prototype started in 2016 and it currently benefits from the collaboration of 24 institutions from 15 countries based in Europe. Emergencies currently covered are those from earthquakes, volcanic eruptions, tsunamis, forest fires, severe weather and flooding. The service is provided 7/24H for any relevant event forecasted or that has occurred worldwide providing reports and verbal interaction within three hours since the activation from ERCC. The final goal is to support the European Union Civil Protection Mechanism in the decision-making when supporting a specific country just affected by a catastrophic natural event. The service is complemented by routine update reports and briefings provided three times a week describing the crisis situation.

On February 6, 2023, ARISTOTLE was activated twice in consequence of the Mw7.8 and of the Mw7.5 earthquakes that occurred at 01:17 UTC and 10:24 UTC, generating very significant losses in Turkey and Syria. The Mw7.8 earthquake marked the first time that the ARISTOTLE system had responded to such a major and impactful event, which also triggered a basin-wide tsunami alert for the Mediterranean Sea. We will present the results obtained by the Earthquake and the Tsunami Hazard Groups of ARISTOTLE and discuss the complexity of assessing the main characteristics of the earthquakes, their impact and the provision of realistic scenarios within three hours from the event occurrence. The expert analysis is based on rapidly available event-specific information (e.g., shakemaps, PAGER), historical earthquakes, weather forecast in the region, tsunami potential, population, infrastructures and buildings exposure. Our experience shows that ready provision of scientific knowledge is crucial to respond more quantitatively to the needs of disaster risk managers in the immediate post-earthquake emergency phase.

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