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COASTAL EFFECTS, TSUNAMI AND SEICHING ASSOCIATED WITH THE KAHRAMANMARAŞ TURKEY-SYRIA TWIN EARTHQUAKES AND AFTERSHOCK SEQUENCE OF FEBRUARY 2023

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ABSTRACT- A strong M7.8 earthquake (02/06/2023; 01:17:36.1 UTC) followed by a second event (M7.5) on the same day (10:24:49 UTC) in Central Turkey caused extensive damage and fatalities (>> 50,000 in Turkey and Syria). Ground shaking exceeding 1.0 g in some locations (USGS, EMSC), structural damage, and multiple secondary effects were documented by Turkish and Greek reconnaissance teams in preliminary reports (e.g., (Lekkas, et al., 2023), reports to the EMSC). The M7+ earthquakes were widely felt in Turkey and in neighboring countries, such as Greece, the Balkan region, and Italy, as far as 1200 km and beyond. Flooding was also reported in few locations, including the bay of Alexandretta and in Salqin, Idlib, Syria. Sea level stations recorded a small tsunami, and tsunami runup was observed in Cyprus and Turkey. Through security cameras and personal cellphone footage, seismic seiches were recorded across Turkey and Cyprus. Some localities even reported multiple incidences of seiches over the course of the earthquake sequence in the same body of water. Observations of seiches are rare in the Eastern Mediterranean and are therefore especially valuable to document. Most importantly, the set of observations collected here is one-of-a-kind dataset (the most extensive dataset in Turkey and a unique dataset of seiche observations for Cyprus). Spatial analysis of seiche observations may also be valuable in documenting areas prone to liquefaction and vice versa, with particular use in the study of older or historical earthquakes. In this paper, we document the coastal effects of the Kahramanmaras Turkey earthquakes, followed by a first-order analysis. Satellite images were also processed to showcase the extent of flooding that followed the large twin earthquakes and lasted at least 3 days around the bay of Alexandretta. The source of flooding likely is a combination of subsidence, liquefaction and the tsunami that ensued. Tsunami amplitudes were small but clearly recorded in few stations; the tsunami's genesis mechanism is in debate.

Keywords: *tsunami; seiche, Turkey, coastal effects, historical tsunami records*

1. INTRODUCTION

On February 6, 2023 (01:17:36.1 UTC), a strong shallow M7.8 earthquake occurred approximately 30 km WNW of Gaziantep city, in Southeastern Turkey (CSEM/EMSC), and about twice that distance from the border with Syria (USGS, EMSC; Figure 1). Hundreds of aftershocks ensued within hours of the mainshock (USGS; the largest M6.7).
The two earthquakes are associated with the Eastern Anatolian Fault zone (EAF; Duman & Emre, 2013), a ~600km sinistral strike-slip fault zone which forms the boundary between the Arabian and the Anatolian plates. It is characterized by a narrow deformation zone to the NNE and a wider deformation zone to the SSW. Although the predominant motion of the EAF is strike-slip, normal or reverse motions are also sometimes observed along the fault zone. The two M7+ earthquakes happened in a region that is seismically active but had been relatively quiescent in the last century ((Sesetyan, Stucchi, Castellli, & Gomez Capera; Taymaz, Ganas, Melgar, Crowell, & Ocalan, 2023) and references therein). According to (Sesetyan, Stucchi, Castellli, & Gomez Capera) preliminary report, about a dozen earthquakes of M6.5 or greater occurred in the last millennium (1000-1900) in the general region of the twin Turkey earthquakes, with the largest one in Antakya in 1822 (Mw7.74). In the 20th century, several M6+ occurred in the EAF, the most recent and largest a Ms6.8 in 1971 (e.g., Sandvol et al., 2003).

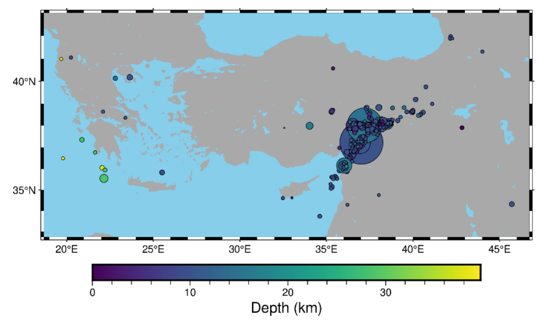


Fig. 1. Seismicity in the month following the M7.8 Pacarzik earthquake (02/06 – 03/15, 2023). Graduated symbols and colors represent magnitude and depth respectively.

The February 6, 2023, earthquakes caused widespread devastation through ground shaking and secondary effects, which included landslides, liquefaction and subsidence (e.g.,(Lekkas, et al., 2023), special reports to EMSC). A tsunami was observed and recorded (see Table 1, Figure 2) by few tide gauge stations on the coasts of Turkey and Cyprus (unfortunately, however, not all tide gauge stations nearby were operating). Additionally, seismic seiching was observed from the main M7.8 earthquake, the M7.5 event, as well as from a large aftershock. In this article, we discuss the coastal effects associated with the twin earthquakes and provide a first order analysis of the water level records and other relevant data collected after the two earthquakes.

Strike-slip faults such as the EAF are generally not associated with tsunamis because a tsunami generating mechanism requires vertical uplift of the water column. However, it is now more widely accepted that strike slip fault earthquakes can sometimes generate tsunamis because multi-segmented strike-slip fault systems with step overs can locally produce vertical uplift or subsidence with the potential of a tsunami (e.g., Estrada et al., 2021). Given the locations of the M7+ earthquakes, the likely cause of this tsunami is rather interesting and a source of a discussion.

Seismic seiches may also be observed during the onset of ground shaking locally, or with the arrival of seismic waves from distant earthquakes (McGarr and Vorhis, 1968; Barberopoulou et al., 2004; Barberopoulou et al., 2006). Seismic seiching is a term used to describe the surface oscillations generated in enclosed or semi-enclosed water basins due to earthquake ground motions (Kvale, 1955; Rabinovich 2009; Barberopoulou et al., 2004; Barberopoulou, 2008;(Bondevik, Gjevik, & Sorensen, 2013). Such oscillations have previously been associated with distant, regional, and local earthquakes. However, through seismic and spatial analyses, it has been suggested 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 sufficient data to understand the occurrence of standing waves due to seismic motions (e.g., 1964 Alaska earthquake; 2002 Denali earthquake).

2. WATER LEVEL DATA AND METHODS

2.1 TSUNAMI OBSERVATIONS

The data used here are tide gauge records from national or global networks and information obtained from global tsunami databases (NOAA-NEIC; IOC-UNESCO; (Danezis, Nikolaidis, Mettas, Hadjimitsis, Kokosis, & Kleanthous, 2020)). Data from tide gauges were obtained from the IOC UNESCO portal for four stations in Turkey (Table 1; Figure 2). The other stations from Cyprus are old piezometric stations not in operation except for one (Lemessos; Danezis, personal communication; (Danezis, Nikolaidis, Mettas, Hadjimitsis, Kokosis, & Kleanthous, 2020)). There are about 10 tide gauge stations within a radius of 350 km from the bay of Alexandretta that are part of national or regional networks; but, unfortunately, not all of them were functional on February 6, 2023. Table 1 and Figure 2 includes a list of operating stations and those that did not record anything because they were down, malfunctioned or are not providing data to the IOC-UNESCO portal due to permanent damage. The tsunami database at NEIC was also searched for complimentary information (Table 2, Figure 3)
personal request and is not available through the IOC-UNESCO portal therefore this estimate may be lower than actual number of stations.

Table 1. List of operating and non-operating stations in the vicinity of the bay of Alexandretta (see Figure 2)

Tide Gauge (name	Country	Longitude	Latitude	Operating on 02/06/2023
Iskenderun	Turkey	36.17676926	36.59423065	Yes
Arsuz (Hatay)	Turkey	35.88519	36.41559	Yes
Erdemli	Turkey	34.25538719	36.56372892	Yes
Tasucu	Turkey	33.83622742	36.28146362	Yes
Bozyazi	Turkey	32.94131088	36.09741974	Yes
Paphos	Cyprus	32.408819	34.755128	No
Zygi	Cyprus	33.338375	34.727083	No
Larnaca	Cyprus	33.640823	34.916181	No
Paralimni	Cyprus	34.036877	35.038288	No
Lemessos	Cyprus	N/A?	N/A?	Yes

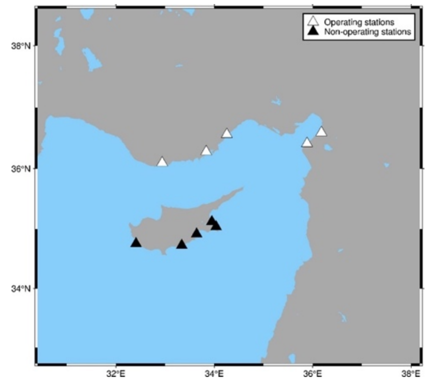


Figure 2. Stations from the IOC-UNESCO portal for which data is available for download for 02/06/2023. White triangles represent stations which have recorded water levels on February 6th, 2023, while black stations were either down or do not have data recorded on the specified date.

Table 2. Tsunami Runup observations as reported by the National Environment Institute (NCEI)

	Country	Location	Latitude	Longitude	Distance from source (km)	First wave arrival (day)	Initial wave arrival (hr)	First Wave Arrival (mins)	Travel (hrs)	Travel (mins)	Max Water Height (m)	Period (first wave in mins)
0	Cyprus	Paralimni	35.03829	34.03688	359	NaN	NaN	NaN	NaN	NaN	0.25	NaN
1	Cyprus	Gazimagusa	35.12320	33.94950	359	6.0	2.0	27.0	NaN	36.0	0.17	NaN
2	Cyprus	Kerinya	35.34100	33.33400	390	NaN	NaN	NaN	0.0	48.0	NaN	NaN
3	Turkey	Erdemli	36.56370	34.25540	257	6.0	2.0	10.0	0.0	48.0	0.13	7.0
4	Turkey	Iskenderun	36.59423	36.17677	100	6.0	2.0	49.0	0.0	25.0	0.12	7.0

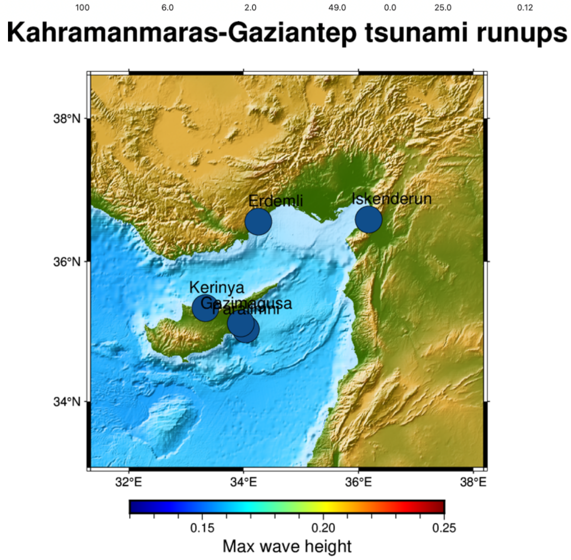
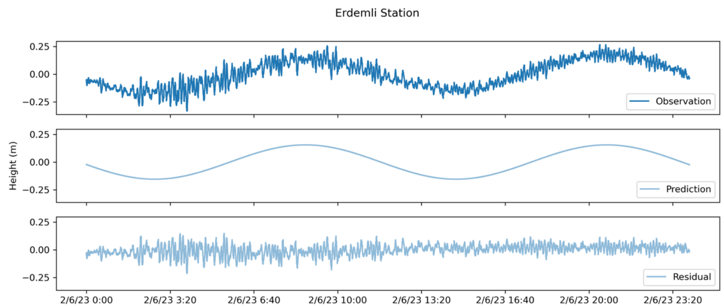


Figure 3. Spatial distribution of tsunami runup data (Table 2) as provided by NCEI.

2.2 WATER LEVEL DATA PROCESSING

Tide gauge records were first decided and then low pass filtered with a 3-pole Butterworth filter to remove high frequencies and recover the longer periods in the recorded signal that are associated with the tsunami (Figure 4, Figure 5). If the predicted
tide did not fit well any of the waveforms (Figure 5), the tide gauge record was further filtered to remove any tidal long period remnants in the signal. The clearest signal above noise in the raw data is evident in the Erdemli and Iskenderun stations, the closest to the epicenter (Figure 4). The maximum wave height (peak to trough) from the stations processed here does not exceed 25cm (Iskenderun station). Fourier spectra of the signals were calculated to show the dominant frequencies in the recorded signals (Figure 5, Figure 6).



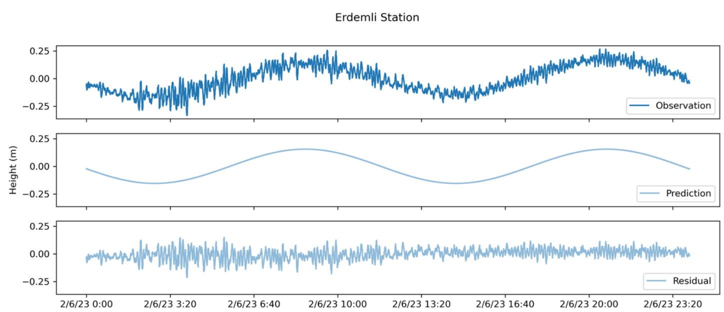


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Figure 4. Raw tide gauge data (24 hours recording starting at February 6th, 2023, 00:00 UTC time)

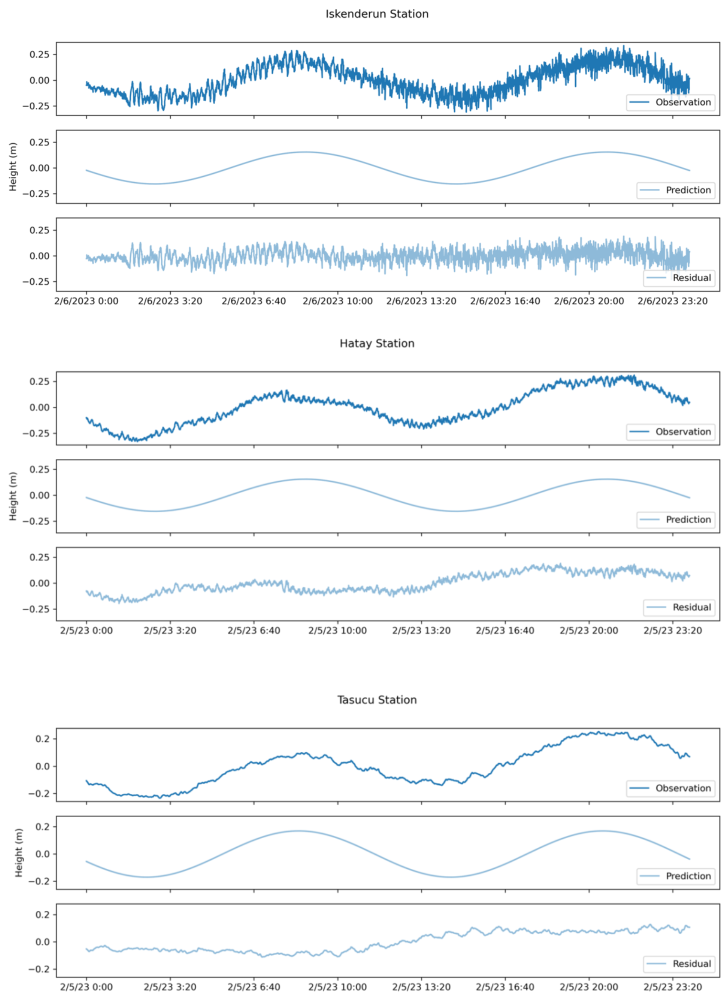

Figure 5. Detided and low pass filtered recordings (from top to bottom) for the Erdemli, Iskenderun, Lemessos, Hatay and Tasucu stations. Only 3 out of the 5 stations listed here recorded a sufficiently strong signal from the tsunami (M7.8 earthquake occurred at UTC 01:17).

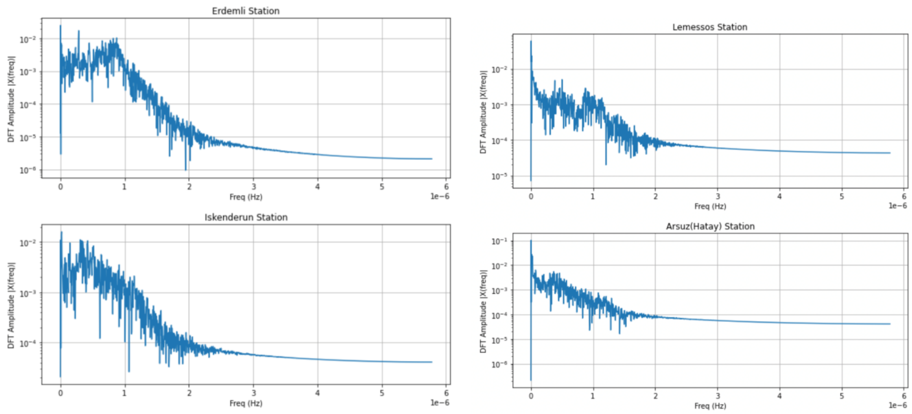

Figure 6. Fourier Spectra of 4 tide gauge stations for which water level records were obtained for the February 6, 2023 earthquake.

3 SEICHING

3.1 OBSERVATIONS

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The data obtained and used here are video recordings of sloshing from eyewitness accounts reported through social media and news agencies, security camera footage, and related information from global database repositories. More than fifteen seiching observations associated with the Turkey earthquakes of February 6, 2023, were collected (Table 3, Figure 7, and Figure 8). The majority of these observations were from swimming pools, while few others appear to be from outdoor water tanks (for irrigation, etc.). Two observations do not fall in the last 2 categories: one was from a fountain and another from a large home aquarium. All the observations, therefore, are from regularly shaped man-made basins (mostly rectangular). Many observations were recorded on pool security cameras because they were at hotels or other commercial buildings where cameras are used widely for security reasons. For this reason, it is more common to find observations from swimming pools as opposed to other water basins. Besides security footage, other videos were recorded on smart phones by witnesses. Observations collected are not associated with the same earthquake. Some observations are associated with the M7.8 earthquake, some are associated with the M7.5 earthquake, and one is associated with one of the large aftershocks (M6.3; 2023-02-20).

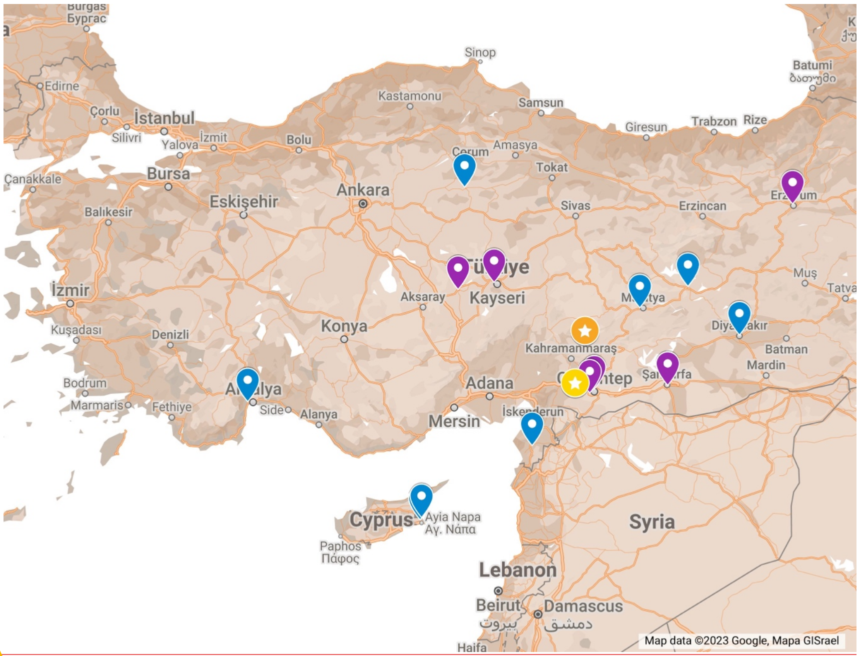

Figure 7. Spatial distribution of seiche observations from the Kahramanmaras earthquake sequence of February 6, 2023, in Turkey. The light and dark yellow stars show the relative location of the M7.8 and M7.5 earthquakes respectively to the observations, which span a 500km-by-500km area. Purple pinpoints represent observations whose locations are well constrained (i.e., with "exact" coordinates), while blue points show those observations where only the town or city could be identified. The observations are from Turkey except for two that are from Cyprus (see Table 3).

Each observation has been assigned a location and associated seismic event to the best of the authors' abilities, and the certainty of each assignment has also been noted (see Table 3). Two observations are from Cyprus and the rest are from Turkey. Videos obtained from the web, show sloshing in non-residential and residential swimming pools (see still images taken from the videos on Figure 8), a fountain, and various other water tanks.

Based on time stamps included in some of the footage from security cameras, we have constrained the time of occurrence for about half of the observations of sloshing. For other observations, times of occurrence have been approximated through correspondence with the video creators. Basedon the times the videos were collected, observations appear to be associated with the M7.8 event (01:17 UTC; 04:17 local time), the M7.5 event at (10:24 UTC; 13:24 local time) in Gaziantep, and with a large aftershock (M6.3) on February 20th, 2023. The spatial distribution of observations collected can be seen in Figure 7, which spans an area of at least 500km x 500km.

Table 3. Seiche observations collected after February 6, 2023.

#	Countr	Locatio	Lat	Lon	Locatio Certaint	Associat Event	Body o Water	Video Type
1	Turkey	Gaziantep	**37.091**	**37.375**	**Exact**	M7.8 (02/06/20 01:17:36.1 UT	Public Swimm Pool	Security came with timer
2	Turkey	Gaziantep	**37.091**	**37.375**	**Exact**	M7.5 (02/06/20 10:24:49 UT	Public Swimm Pool	Security came with timer
3A	Turkey	Antalya	36.893	30.61	Approx.	M7.8 (02/06/20 01:17:36.1 UT	Residential Swimming Po	Personal cellph
3B	Turkey	Antalya	36.893	30.61	Approx.	M7.8 (02/06/20 01:17:36.1 UT	Residential Swimming Po	Personal cellph
4	Turkey	Antalya	36.893	30.61	Approx.	M6.3 (2023-02 17:04:29)	Residential Swimming Po	Personal cellph
5	Turkey	Antakya	36.204	36.162	Approx.	M7.8 (02/06/20 01:17:36.1 UT	Public Swimm Pool	Security Cam
6	Turkey	Nevşehir	**38.623**	**34.717**	**Exact**	M7.5 (02/06/20 10:24:49 UT	Public Swimm Pool	Personal cellph
7	Turkey	Kayseri	**38.733**	**35.422**	**Exact**	M7.5 (02/06/20 10:24:49 UT	Public Swimm Pool	Security came with timer
8	Turkey	Şanlıurfa	**37.149**	**38.81**	**Exact**	M7.5 (02/06/20 10:24:49 UT	Public Swimm Pool	Security came with timer
9A	Turkey	Erzurum	**39.918**	**41.248**	**Exact**	M7.5 (02/06/20 10:24:49 UT	Public Swimm Pool	Personal cellph
9B	Turkey	Erzurum	**39.918**	**41.248**	**Exact**	M7.5 (02/06/20 10:24:49 UT	Public Swimm Pool	Personal cellph
10	Turkey	Elazig	38.671	39.204	Approx.	M7.5 (02/06/20 10:24:49 UT	Fountain	Personal cellph
11	Turkey	Alaca (Çorur	40.17	34.842	Approx.	M7.5 (02/06/20 10:24:49 UT	Outdoor Tan	Personal cellph
12	Turkey	Malatya	38.346	38.266	Approx.	M7.8 (02/06/20 01:17:36.1 UT	Irrigation Ta	Security came with timer
13	Turkey	Malatya	unknown	unknown	unknown	unclear	Commercia Swimming Po	Personal cellph
14	Cyprus	Paralimni	35.065	33.975	Approx.	M7.8 (02/06/20 01:17:36.1 UT	Residential Swimming Po	Personal cellph
15	Cyprus	Paralimni	35.063	34	Approx.	M7.8 (02/06/20 01:17:36.1 UT	Non-rectangu Swimming Po	Personal cellph
16	Turkey	Diyabakir	37.925	40.211	Approx.	M7.8 (02/06/20 01:17:36.1 UT	Aquarium	Personal cellph

Table 3 continued.

#	Access video	Notes
1	https://www.youtube.com/watch?v=m8pFB731vy0	First of two observations in same pool in Gaziantep
2	https://www.youtube.com/watch?v=m8pFB731vy0	Second of two observations in same pool in Gaziante
3A	https://twitter.com/Faworimm/status/16224143626 02464	Appears to be taken at dawn. Time of recording uncl
3B	https://twitter.com/Faworimm/status/16224206252 49570	Appears to be taken at dawn. Time of recording uncl
4	https://twitter.com/Faworimm/status/16277230420 70775	Video posted on 2023-02-20, seems to be from aftershock.
5	https://www.youtube.com/watch?v=c9qI-KZmt9g	Large waves in backyard pools
6	https://www.youtube.com/watch?v=iWq9rJYnWbg& =PLi5AeW_TpchzYZjWVuDJGJIJF2WCVtFQE&index=1	Water level is much lower than other pools, so easy t observe amplitude of the waves
7	https://www.youtube.com/watch?v=oEbmcHEmc2s =PLi5AeW_TpchzYZjWVuDJGJIJF2WCVtFQE&index=4	Video features multiple angles of same observation, a location is large sports facilty. Footage is sped up.
8	https://www.youtube.com/watch?v=IoCZvKdg6E8& PLi5AeW_TpchzYZjWVuDJGJIJF2WCVtFQE&index=2	Likewise, multiple angles of same observation becau sports facilty has multiple cameras
9A	https://www.youtube.com/watch?v=PJ0pg9aN648& PLi5AeW_TpchzYZjWVuDJGJIJF2WCVtFQE&index=6	Waves run along the length of the pool; lane dividers to clearly see wave movement
9B	https://www.youtube.com/watch?v=oxqfhtQ6_fc&l Li5AeW_TpchzYZjWVuDJGJIJF2WCVtFQE&index=7	Waves run along the length of the pool; lane dividers to clearly see wave movement
10	https://youtube.com/shorts/5VHxXjBxITk?feature=s	Fountain has ice, outside. Assigned location is not certain, may be erroneous
11	https://youtube.com/shorts/23buzravb9c?feature=s	Snowing, outside. Comment: "Çorum alaca da sarsin aninda havuz" (The pool at the time of the shaking in Çorum, Alaca)
12	https://www.youtube.com/watch?v=9mjE1zPdUn0	Snowing, outside. Large elevated irrigation tank at fa
13	https://www.youtube.com/shorts/5rYU_OIlgXc	Because of video angle, diffcult to see wave motion directly; however, can see water spilling out of pool.
13	https://www.youtube.com/shorts/5rYU_OIlgXc	Because of video angle, diffcult to see wave motion directly; however, can see water spilling out of pool.
14	https://www.tiktok.com/@suheiltel/video/7196862 52400897	Pool lit with underwater lights. Personal villa near co of Cyprus.
15	https://www.facebook.com/watch/?v=8779257233	Includes following comments in English on intensity

	0&extid=NS-UNK-UNK-UNK-AN_GK0T-GK1C&mibextid=2Rb1fB&ref=sharing	associated with this seiche: "On February 6, 2023, at a.m. the disaster began in Turkey and the shockwave quickly reached the island as well. It rocked us all an woke many of us up. It felt like a 4.8 and lasted a lon time. Then the aftershock of 6.3 degrees was felt and recorded at 3.28. So it was a continuous swing. All m stuff hanging on the walls waltzed "nicely" for more 10 minutes, but everything stayed in place in the cupboards and on the shelves. No property damage w recorded on the island, at least not reported, but imag have already emerged of swaying chandeliers and po that have been hit by small waves. "
16	https://www.youtube.com/watch?v=TgUAevXStiQ	Because of glass fish tank, can clearly observe side profile of seiche instead of only from top as in other observations. Wave motion changes over course of earthquake.

The authors have made a general estimate of the periodic motion in each observation by using time stamps from the videos. The periods of oscillations vary depending on the dimensions of the body of water and the forcing exerted to it. Seiches were observed in three main categories of environment: public pools, residential pools, and outdoor water tanks. Of these three, it is easiest to determine the dimensions of public pools, as pools used for exercise and competition are typically standardized to 25m or 50m in length and allocate approximately 2.5m in width to each lane used for lap swimming (source: World Aquatics previously known as FINA). Residential pools are generally much smaller, and it is harder to estimate their size because there are no standard dimensions; however, it is still possible to estimate their size with a good degree of accuracy through comparison with other objects pictured in the video. Harder still, it is even more difficult to determine dimensions of water tanks, though it is likewise helpful to use other objects nearby to roughly estimate size. It is also important to consider whether sloshing is along the length or width of the body of water.

Quick estimations of the motion using the clock on the camera of some of the observations (Figure 8 (Left)) shows the periodic motion to be in the range of 3-5 seconds. Public swimming pools typically span either 25m or 50m in length and allocate approximately 2.5m in width to each lane. Taking observations 1 and 2 into consideration (Table 3), this public swimming pool in Gaziantep seems to be 25m long, 12.5m wide and with 5 lanes. If we use the simple formula (1) with these dimensions in mind, then the primary mode of oscillation for an Olympic sized swimming pool (L=50m) and its half equivalent (25m) are 11 and 5.5 seconds, respectively.

Figure 8. (Left) is a still image of a swimming pool sloshingalong the short side of Gaziantep. Clock on the upper left shows Monday 13 13:12 which is the local time close to the onset of the M7.5earthquake, (Right) Still image of swimming pool sloshing along the short side in Antalaya.

Figure 8. (Left) is a still image of a swimming pool sloshingalong the short side of Gaziantep.

Because sloshing appears to be on the short sides of various sized swimming pools (25 m, 12.5 m, 6m; sloshing appears in both cases to be along the width and not the length) the primary mode of oscillation can also occur at 2.7 seconds for the smallest sized pools. The second and third estimates (5.5, 2.7 seconds) match the approximate calculation from the video recordings in Figure 8 and therefore we can safely assume the sizes of the swimming pools are about half the
size of an Olympic swimming pool (25m x 12.5) or smaller. Videos suggest the mode of oscillation to be primary (rising on one side and fall on the other) in most cases.

$$T=2LNgD \quad N = 1, 2, 3, \ldots (1)$$

3.2 SEICHING HISTORY IN THE EASTERN MEDITERRANEAN (GREECE, TURKEY AND CYPRUS)

Information about seismic seiching in Greece, Turkey, or Cyprus may be found in national, regional or international databases for tsunamis – for example, the NOAA National Centers for Environmental Information (NCEI; Global Tsunami Database (previously NGDC) and regional earthquake catalogs, which discuss historical records with respect to earthquakes and tsunamis (e.g., Papazachos & Papazachou, 2003; etc.). More specifically if Turkey, Greece, and Cyprus are selected as the region of interest in NCEI, only 4 events are included as events with seiche observations (1 from Turkey and 3 from Greece) as seen below:

Table 4. Seiche observations in the eastern Mediterranean (Greece, Turkey) from the NEIC database

Year	Mo	Dy	Hr	Mn	Event Validi	Cause Code	Earthq ake Magni de	Count	Locati	Latitu	Longit de
1636	9	30	18	30	0	1	7.2	Greec	Ionian Sea	38.1	20.3
1810	2	16	0	1	0	1		Greec	Crete	35.5	25
1857	9	17	22	0	0	1		Turke	Marm a Sea	40.2	29
1949	7	23	15	3	3	1		Greec	Chios	38.718	26.482
1979	5	15	6	59	0	1	5.6	Greec	Crete	34.53	24.437

Specifically, no data exists in the Global Tsunami Database concerning seiching in Cyprus; furthermore, one event in Chios appears to be a seiche which was generated from a tsunami, and one observation is from Turkey. Two more observations are listed from Greece (Table 4). It is evident that seiching observations are a rarity in this region of the Eastern Mediterranean. To the best of our knowledge, the observations from Turkey in Table 4 are unique or of very few documented seiches stemming from earthquake ground motions. The dataset which is presented in Table 3 is therefore of particular significance as it is unique for both Cyprus and Turkey.

The observations listed in Table 3 are the only seismic seiches that — to the best of authors knowledge — have ever been collected from Cyprus, making them especially valuable. Recorded seismic seiches from Turkey and Greece are also very few, and the dataset presented from the February 6 earthquake sequence appears to be the most extensive dataset about seismic seiches from Greece, Turkey and Cyprus to have ever been collected.

4. COASTAL FLOODING

Following the February 6, 2023, earthquakes, Iskenderun in the Hatay province was flooded. Iskenderun in the bay of Alexandretta is a coastal low-lying city in Southern Turkey (Demirkesen, 2012). Eyewitness accounts show a flow depth of knee-equivalent (~ a ft or 0.3 m,refs) for the flooding that occurred in the coastal areas of Iskenderun (Figure 9). Using eyewitness accounts, field survey results from reconnaissance reports (e.g., Figure 9, (Lekkas, et al., 2023)), we have delineated the approximate extent of flooding (230 sq km; Figure 10).

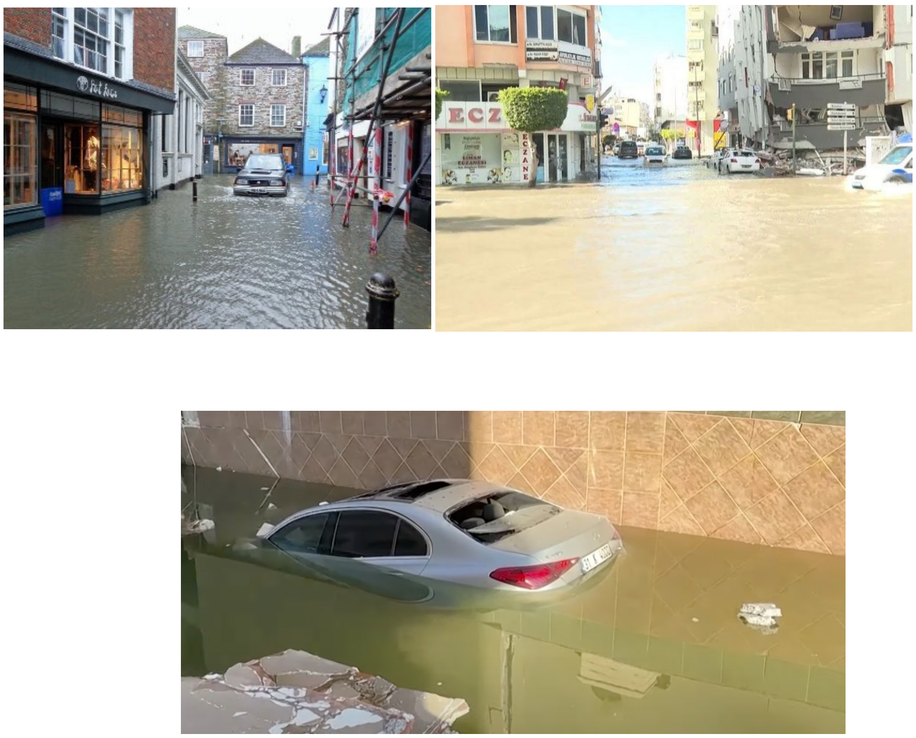

Figure 9. Photographs of the extent of the flooding from Armenia News (upper left). Trend News Agency (upper right), and Reuters (bottom)

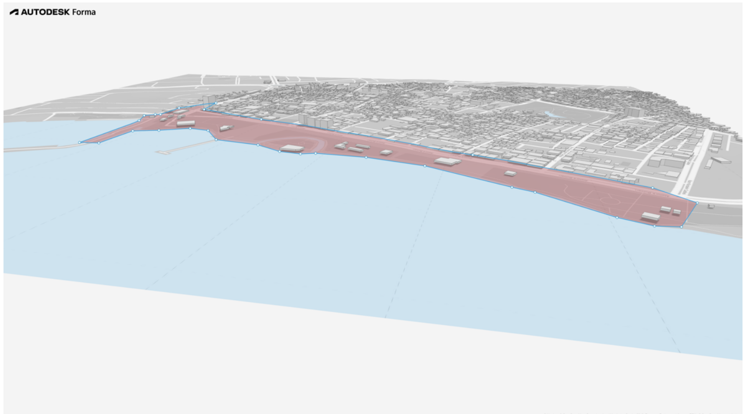

Figure 10. View of the flooded area (approximate extent) in red color in Iskenderun looking SSE, superimposed on a DTM. Extent of flooding was estimated from processed satellite imagery, eyewitness accounts, and reconnaissance reports to the EMSC (e.g. Lekkas et al. 2023)

For a more precise inundation map, we used Landsat 8 and Sentinel 2 data. The satellite images used here were taken before and after the main M7.8 event as close to the date of the earthquake as possible (Sentinel 2 images: 01/25/2023 and 02/09/2023; Landsat 8 images: 02/05/2023 and 02/06/2023). A true color composite of the Bay of Alexandretta post-earthquake (02/09/2023) is shown in Figure 11.

Figure 11. True Color Composite of the Bay of Alexandretta from the 9th of February 2023 using Sentinel 2 B-G-R bands. Red box shows Iskenderun. Flooded area was primarily on the SSW side within the box.

Because the extent of flooding is quite small (~230 sq km), we employed several different methods to capture the extent of inundation. A small extent of flooding may be difficult to capture from the processing of images of moderate resolution as is the case with Landsat 8 (30m). Specifically, true and false color composites and 2 different water indices were employed for this purpose. Landsat 8 bands 3 and 5 (30m resolution) were used in addition to Sentinel 2 Green and NIR bands (bands 3 and 8 respectively; 10m resolution).

NDWI (Normalized Difference Water Index) was used to delineate the extent of flooding observed after the earthquakes of 02/06/2023. The NDWI method is commonly used for delineating and monitoring content changes in surface water. NDWI formula is defined as follows:

$$NDWI = Green - NIRGreen + NIR \quad (2)$$

The following values were used as a guide to interpret results: *0,2 - 1 for water surface, 0.0 -0.2 for flooding/humidity, -0.3-0.0 for moderate drought/non-aqueous surfaces, -1 - - 0.3, Drought/non-aqueous surfaces*.

Using Landsat 8 images of the bay of Alexandretta captured on the 5th and 6th of February 2023, we see in Figure 12 prominent water presence on the date of the Kahramanmaras earthquake (green color). More specifically, prior to the earthquake sequence of February 6, 2023, NDWI shows a general drought in the area (orange shades) and a very low water content on the ground. The next day, the index shows a large presence of water content throughout the classified image, and around the area that corresponds to Figure 10 (see red arrow pointing to green strip along the coast on Figure 12). Note that some of the water content in Figure 12 (green) is related to the snow that appears on Figure 11 and other causes.

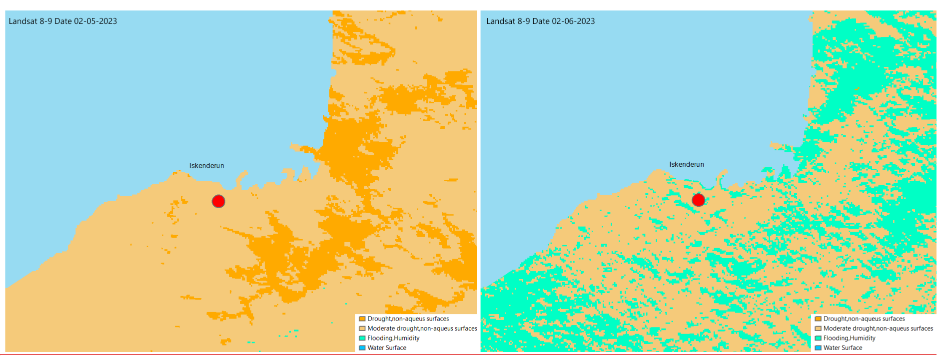

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Figure 12. Before and after NDWI for Iskenderun and neighboring areas. Red dot shows central point location of flooding observed after the M7.8 February 6, 2023 earthquakes.

5. DISCUSSION/CONCLUSIONS

The coastal effects associated with the twin earthquakes of February 6, 2023Kahramanmaras Turkey earthquakes have been presented. Tsunami recordings from public portals i.e. IOC-UNESCO, were detided and fourier spectra of their frequency content were estimated. A clear tsunami signal was recorded only in a small subset of operating tide gauge stations including some in Cyprus. The best records were those closest to the Bay of Alexandretta. The tsunami records are rather interesting because of the location of the earthquake and its focal mechanism. Subsidence and liquefaction observed in Iskenderun likely have contributed to the flooding observed in the area but the degree each of these factors has played in the flooding is difficult to estimate.

A unique and one-of-a-kind dataset of seiche observations collected from Turkey and Cyprus have also been documented. The seiche observations collected after the February 6, 2023 events are especially valuable for many reasons:

- The dataset is the largest set of seiche observations that authors are aware of for the eastern Mediterranean region.
- Seismic seiche observations from Cyprus are the only ones that authors are aware of to have been documented.
- Seismic seiches are associated with multiple events from the February 6, 2023 earthquake sequence.
- A relatively large set of seismic seiches collected may allow for spatial analysis.
- Seiches may be associated with locations of liquefaction and vice versa which could further help hazard studies of past of future earthquakes of significance.

Satellite imagery from before and after the main event of February 6, 2023, from Landsat 8 and Sentinel were processed to help in delineating flood extent from the Kahramanmaras earthquakes. Specifically, Landsat 8 in combination with eyewitness accounts from media (e.g., newspapers, online), reports to the EMSC (Lekkas et al., 2023) were used to delineate the extent of flooding caused by the main M7.8 02/06/2023 event. The extent of flooding was estimated to about 230 sq km which is small and presented challenges in its exact estimation from open-source satellite imagery of moderate resolution (10-30m). Eyewitness accounts, videos and images collected from online media which were geolocated helped to delineate the extent of flooding. The causes of flooding have not been investigated in this study but likely are attributed to more than one factor such as subsidence, tsunami and liquefaction.

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