MINISTRY of INFRASTRUCTURES and TRANSPORTATION
EARTHQUAKE PLANNING & PROTECTION ORGANIZATION (EPPO)
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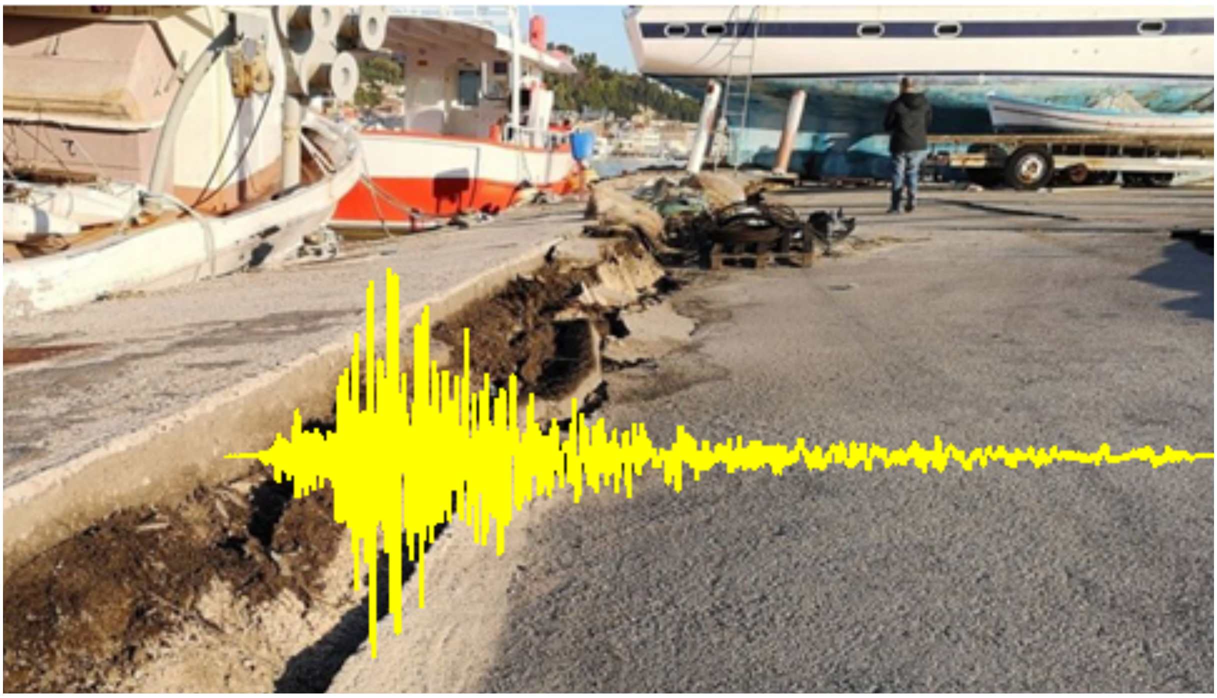
S. IONIAN SEA EARTHQUAKE M 6.8 ON 25/10/2018

STRONG GROUND MOTION AND EFFECTS ON SOIL AND BUILT ENVIRONMENT



THESSALONIKI
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1. INTRODUCTION

On October 25, 2018, 22:54GMT (October 26, 01:54 local time), a strong earthquake occurred in the southern Ioanian sea of magnitude M6.8(USGS, GFZ). According to the Hellenic Unified Seismographic Network it was a shallow crustal event with an epicenter to the south of Zakynthos island coast. The coordinates of the mainshock, according to EMSC (https://www.emsc-csem.org/Earthquake/earthquake.php?id=720235#) were 37.53°N 20.62°E.

The spatial distribution of the intensity based on the response of citizens of the broader area (DYFI: Did You Feel It?), is shown in Figure 1. The highest observed macroseismic intensity in the southern coasts of Zakynthos was I_{MM}=VI+. The mainshock was strongly felt in the western Peloponnese and Kefalonia. It was also felt in Crete, Attica, Thessaly, Macedonia, Albania, Dalmatic coasts, southern Italy and southwestern coasts of Turkey.

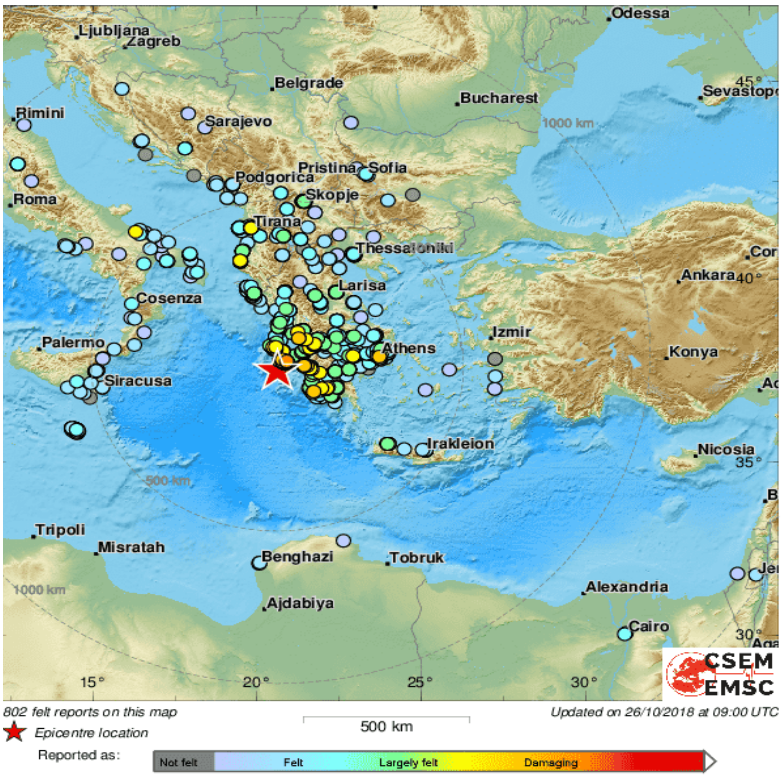

Figure 1. Distribution of the macroseismic intensity (colored circles, DYFI) according to the response of citizens in the broader epicentral area; red star the earthquake epicenter (EMSC-CSEM).

The focal mechanism of the earthquake of the October 25, showed that it is related with a thrust fault with significant strike slip component. In Figure 2 focal mechanisms published by national and international seismological institutes are given. In Table I, the parameters of the respective focal mechanisms are also provided for both nodal planes.

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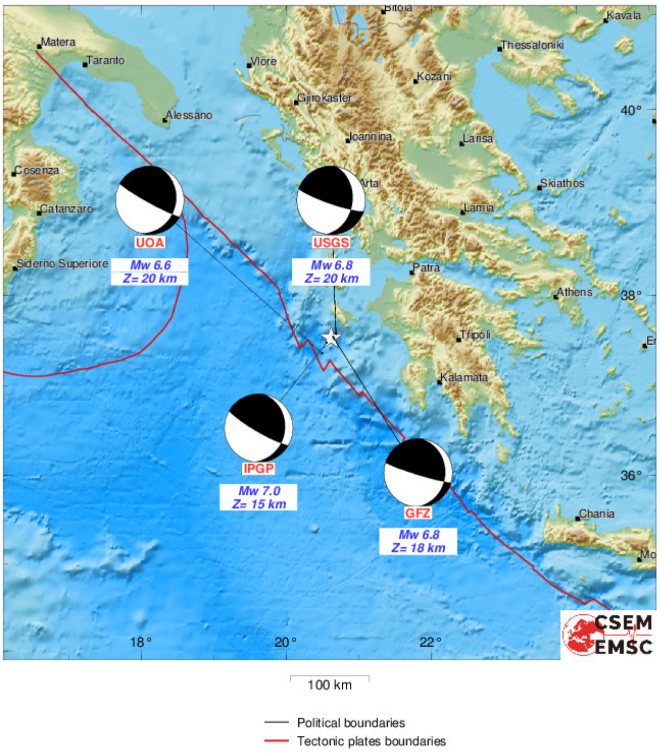


Figure 2. Graphical representation of focal mechanism solutions of the October 25, 2018 earthquake.

Table I. Focal mechanism solutions of the October 25, 2018 earthquake.

NODAL PLANE 1			NODAL PLANE 2			INSTITUTE
ζ°	δ°	λ°	ζ°	δ°	λ°	
107	85	68	5	23	167	GFZ
120	81	67	10	24	158	IPGP
119	84	66				UoA
109	81	51	8	38	166	USGS

2. AFTERSHOCK ACTIVITY

The aftershocks' distribution with M≥3.5, by Nov. 8, 2018, are shown in Figure 3. Data are taken from the Geodynamic Institute of the National Observatory of Athens (http://bbnet.gein.noa.gr/HL/seismicity/catalogues/manual-alerts). In the same figure the strongest aftershocks (**M**≥5.0) of the 1997 seismic sequence are also shown. From the distribution of the aftershocks it seems that they are related with the Zakynthos seismic fault proposed by Papazachos and Papazachou (2003), with a total length of about 55km.

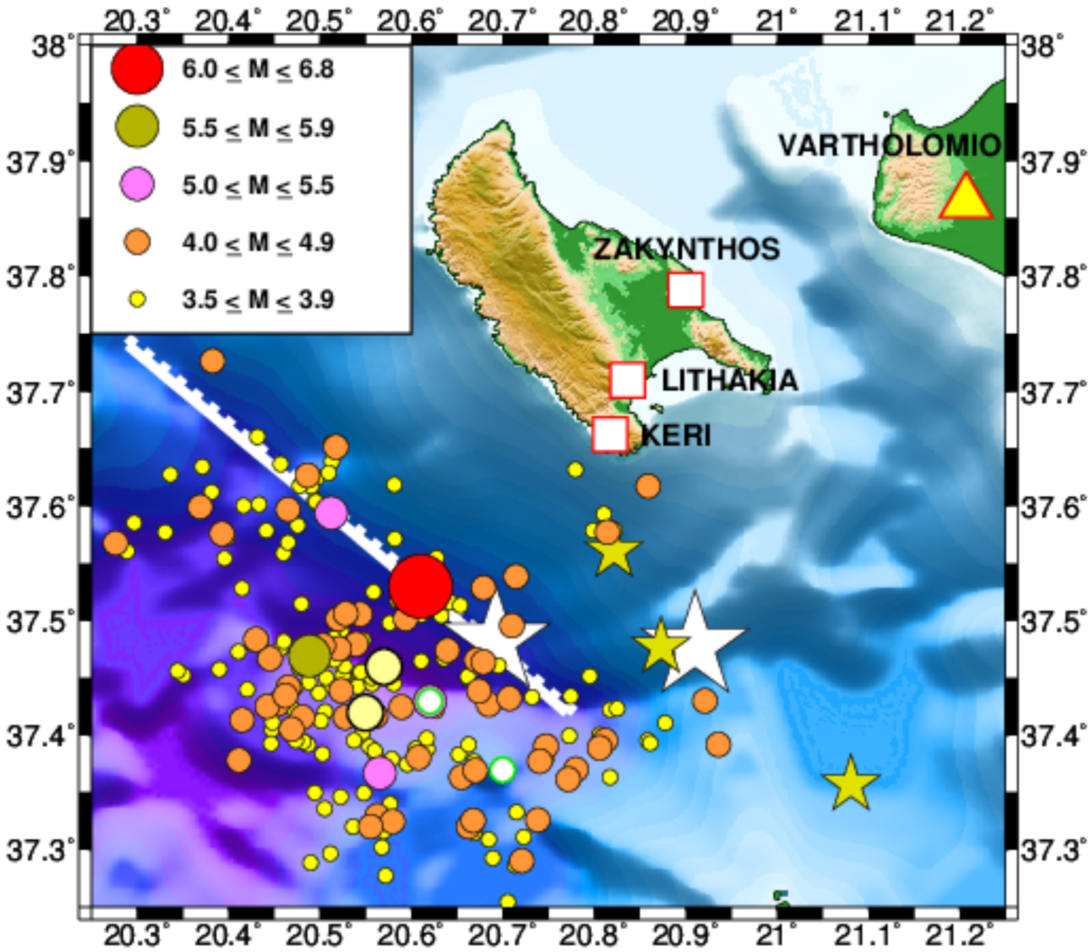
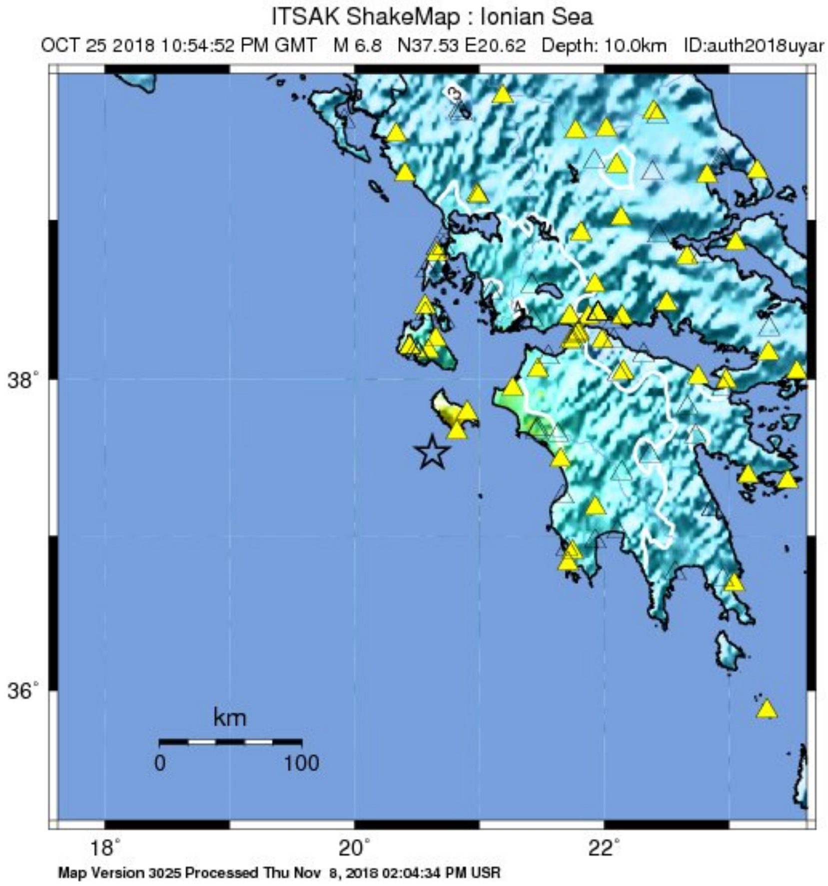


Figure 3. Distribution of the recent seismic aftershoks with magnitude **M**≥3.5, by Nov. 8, 2018, (the mainshock M6.8, in red circle). Epicenters of aftershock events of the 1997 seismic sequence with **M**≥5.0, are represented with stars. The main thrust fault proposed by Papazachos and Papazachou 2003, is given by a white line, while accelerographs in the 'near field' by white squares.

3. SHAKEMAPS

The research unit ITSAK-EPPO, has deployed a dense accelerometric network throughout Greece, recording the ground motion in continuous mode 24/7.The accelerographs are CMG-5TDE της Guralp Systems Ltd., equipped with broad band sensors, 24bits data logger and GPS absolute time. Data are transmitted at ITSAK-Thessaloniki premises in real time. Based on this data in combination with selected ground motion prediction equations, automatically produced in almost real time relevant shakemaps and uploaded on the web (www.itsak.gr). In Figures 4 and 5, the updated shakemaps incorporating recordings from the Geodynamic Institute as well, are presented. A qualitative comparison between instrumental macroseismic intensity (Figure 4) and the corresponding DYFI intensity presented in Figure 1 shows a satisfactory agreement with a few exceptions mainly in long epicentral distances.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Worden et al. (2011)

Figure 4. Distribution of instrumental macroseismic intensity 'shakemap'; an updated version incorporating recordings from the Geodynamic Institute of the National Observatory of Athens. The epicenter is shown by a star and the recording accelerograph stations by triangles.

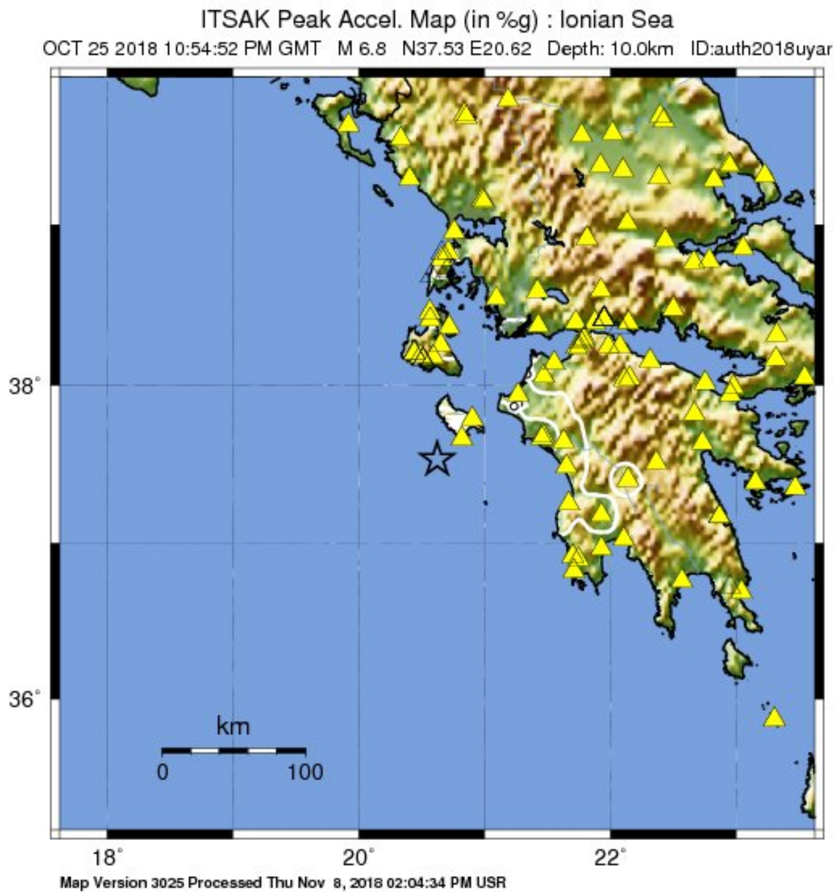


Figure 5. Distribution of peak ground acceleration 'shakemap'; an updated version incorporating recordings from the Geodynamic Institute of the National Observatory of Athens. The epicenter is shown by a star and the recording accelerograph stations by triangles.

4. STRONG GROUND MOTION RECORDS OF THE OCT. 25, 2018 (M6.8) EARTHQUAKE AND THEIR ANALYSIS

On the Zanynthos island there are two accelerographs installed and maintained by ITSAK; one in the town of Zakynthos and another in the village of Keri, the closest one in the mainshock epicenter (~22km).

4.1 Geological, geotechnical and geophysical data for stations ZAK2 και KRI1

According to the geological map of I.G.M.E for the island of Zakynthos (Figure 6 – scale 1:50.000), ZAK2 station is mounted on recent alluvial deposits. These are composed mainly from sandy clays and clayey silts of low plasticity and medium stiffness as well as layers of sands having low-to-medium density. Regarding the geological setting at the location of station KER1, the main formations consist of marly limestones.

Geophysical field measurements, referring to Cross-hole (CH) and Down-hole (DH) tests, were performed close to ZAK2 station in the framework of a research program in 2004 (EPPO 2004). The above tests resulted in a shear wave velocity (Vs) profile shown in Figure

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7. The EC8-based value of Vs along the first thirty meters ($Vs_{,30}$) of the soil medium may be estimated in the range of 200-250m/sec. With reference to KER1 station, the corresponding value of $Vs_{,30}$ was estimated by means of geology and slope of the topographic relief proxies (Stewart et al. 2014), leading to 500-550m/sec.

Following up on the above data for KRI1 and ZAK2 stations, Table III summarizes the main parameters related to the seismic hazard zone and the soil category at KRI1 and ZAK2 stations, according to EC8 and the Greek Seismic code (EAK2000/2003). The corresponding code-defined elastic response spectra are compared in the ensuing with those computed from the earthquake recordings at the two stations.

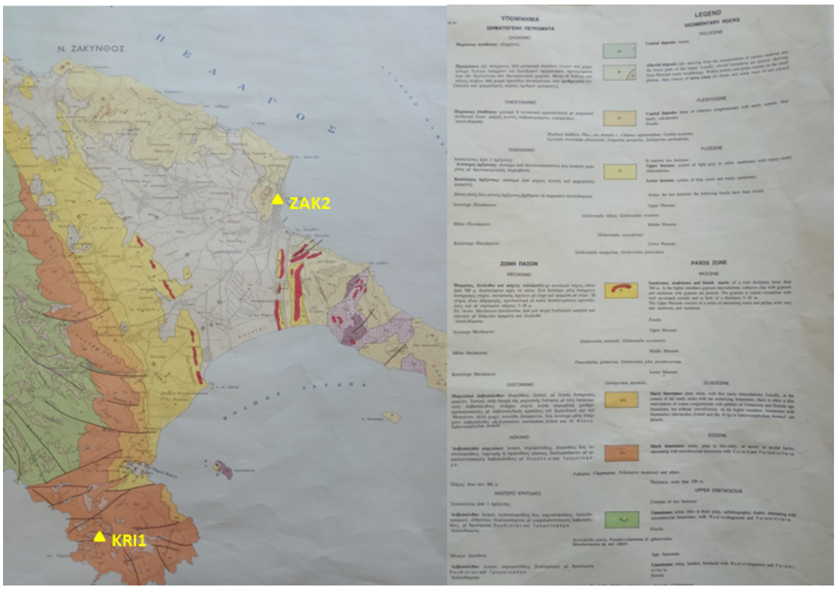


Figure 6: Part of the geological map of I.G.M.E for the island of Zakynthos (scale 1:50.000).

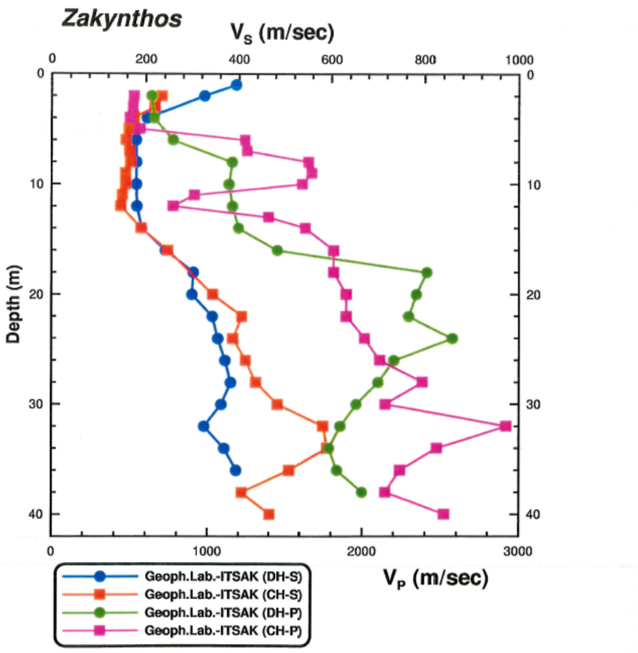


Figure 7: Distribution of P and S wave velocity with depth derived from geophysical field measurements (DH και CH) (EPPO 2004)

Table III: Seismic hazard zone parameters and soil category at KRI1 and ZAK2 stations according to the seismic codes EC8 and EAK20002003 (Greek Seismic Code)

STATION	STATION LOCATION	SEISMIC HAZARD ZONE	SOIL CATEGORY ACCORDING TO EC8	SOIL CATEGORY ACCORDING TO EAK2000/2003
ZAK2	Telecommunications Building of Zakynthos (37.7879°N, 20.9000°E) (Distance from source: 30.2 km)	III $A=a_{g,R}$ = 0.36g	C ($V_{s30,m}$ = 200-250 m/s)	Γ
KRI1	Keri (south of Zakynthos) (37.6622°N, 20.8172°E) (Distance from source: 25.0 km)	III $A=a_{g,R}$ = 0.36g	B ($V_{s30,p}$ = 500-550 m/s)	B

$V_{s30,m}$: based on in-situ measurements of shear wave propagation velocity (V_s)
$V_{s30,p}$: based on geology and slope of the topographic relief proxies (Stewart et al. 2014)

4.2 Strong motion records in ZAK2 and KER1

Processing of the ZAK2 and KRI1 accelerograms was made using the software SCREAM&ART3 Guralp Systems Ltd. A s well as the VIEWwave (Kashima, 2016). The results in term of peak ground acceleration, velocity and displacement values are given in Table III. In Figs. 8 and 8, acceleration, velocity and displacement tiome histories are shown, together with their corresponding acceleration, velocity and displacement response spectra (damping h=5%). The Arias intensity and an estimated significant duration of ground motion is provided in Figure 10. Fourier spectra of the ZAK2 and KRI1 recordings shown in Figure 11, exhibit a corner frequency, fc~0.1sec, close to the one expected for such a magnitude event. The estimated displacement particle motion presented in Figure 12 shows an almost north-south motion of about 15cm in ZAK2 and 17cm in KRI1 station.

The most important observations in the aforementioned recording processing results can be summarized as follows:

- In the village of Keri (KRI1) the maximum PGA~0.36g was observed, similar to the one proposed for the zone III of the Greek Seismic Code, while for the Zakynthos town the observed PGA~0.17g, is almost half of the same seismic zone.
- ~0.8g, in natural period T~0.4sec, were observed.
- The maximum peak ground velocity, PGV, in both stations was of the order of 17cm/sec, although their corresponding PGA values showed large difference.
- The estimated significant duration ranged between 15sec to 30sec in Keri and Zakynthos, respectively.
- The observed corner frequency of the mainshock, fc~0.1sec, was expected for an earthquake of M6.8.
- The displacement partical motion exhibited on the island a main north-south direction, with maximum values ~17cm in Keri and ~15cm in Zakynthos town.

Table III. Peak ground acceleration, velocity and displacement values for the Oct. 25, 2018 mainshock (M6.8), observed at the station ZAK2 and KRI1.

STATION	COMPONENT	Peak Ground Acceleration (cm/sec^2)	Peak Ground Velocity (cm/sec)	Peak Ground Displacement (cm)
ZAK2	NS-comp	154	14.4	8.4
	EW-comp	165	16.4	5.5
	Z-comp	71	9.8	7.7
KRI1	NS-comp	111	13.2	10.6
	EW-comp	356	17.2	4.4
	Z-comp	159	7.3	6.8

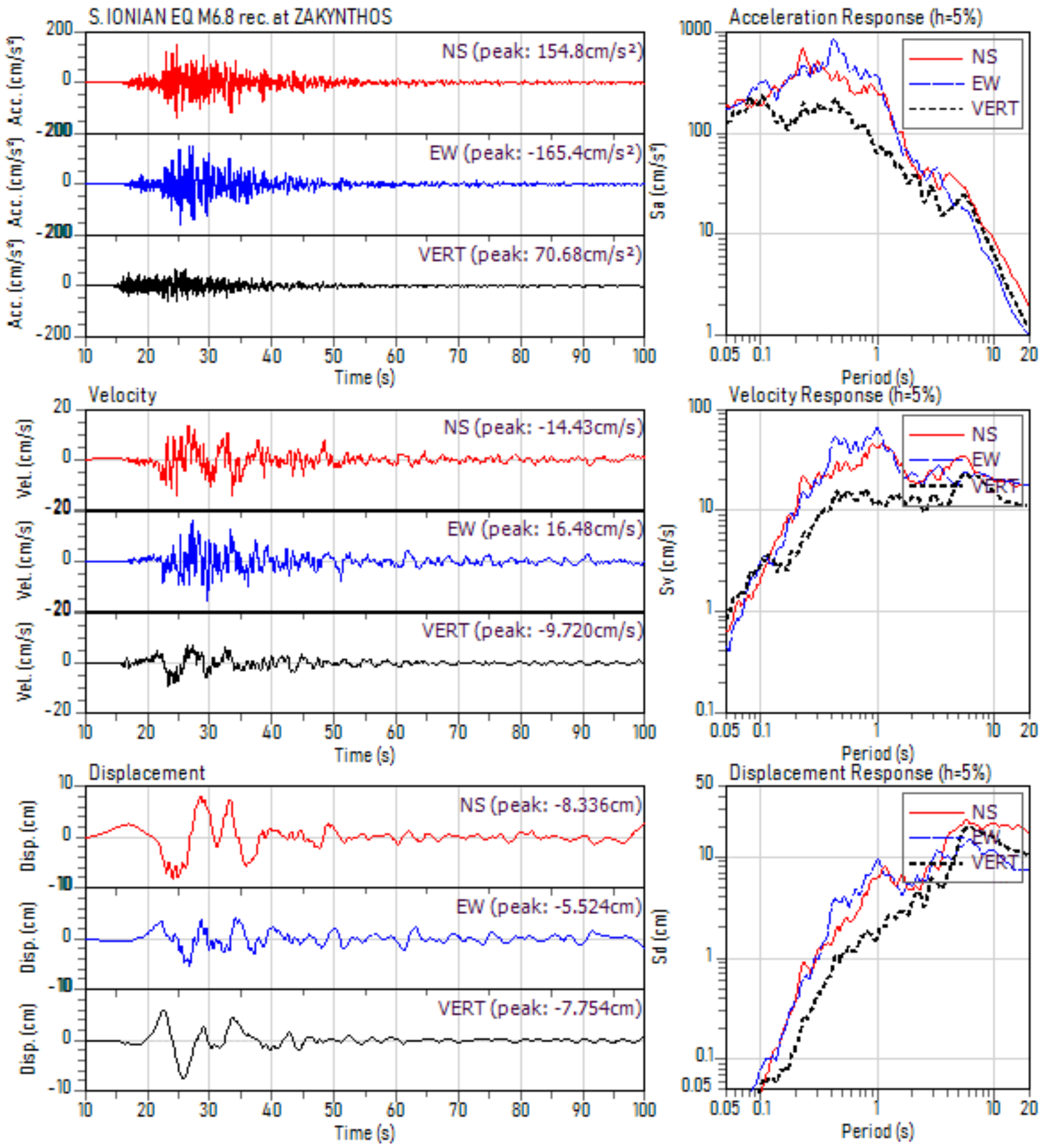


Figure 8. Time histories of acceleration, velocity and displacement for the 3-component recordings in the Zakynthos town station (ZAK2), and their corresponding acceleration, velocity, displacement response spectra.

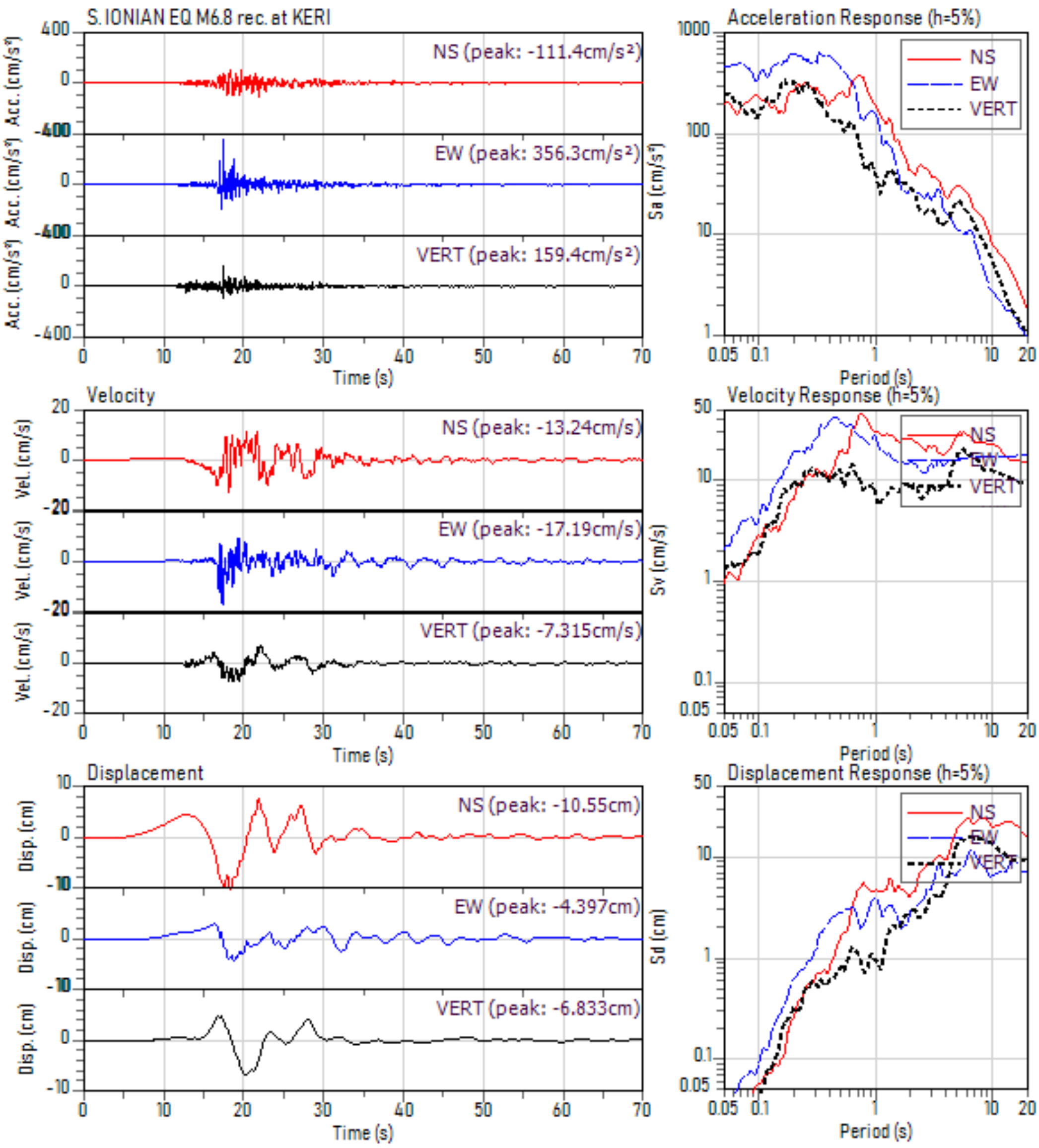
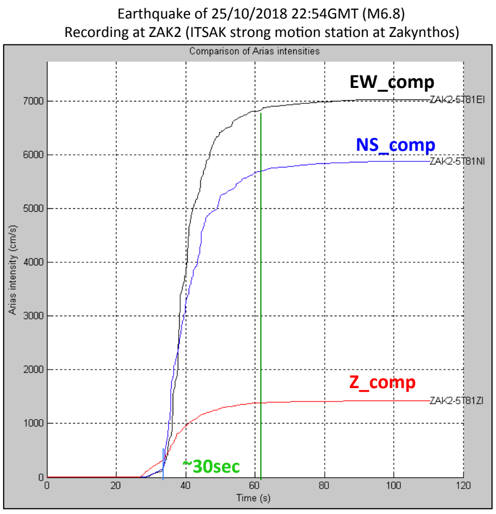


Figure 9. Time histories of acceleration, velocity and displacement for the 3-component recordings in the Keri-Zakynthos station (KRI1), and their corresponding acceleration, velocity, displacement response spectra.



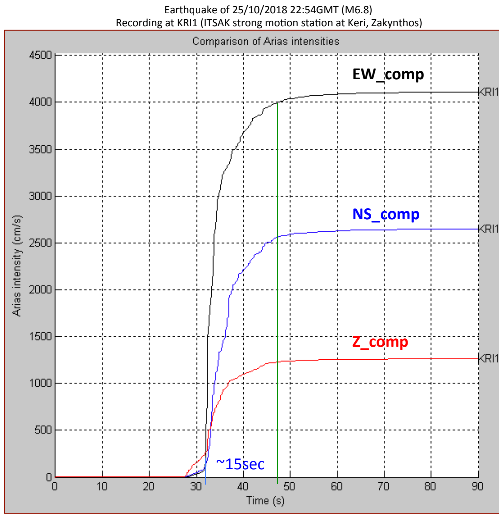
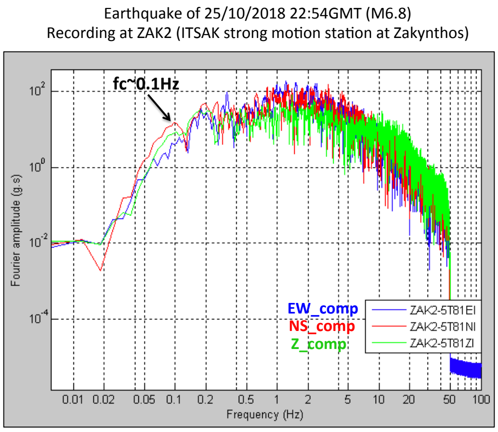


Figure 10. Arias Intensity and estimated significant duration of strong ground motion for the 3 components of the acceleration time history in Zakynthos town (ZAK2, left) and Keri (KRI1, right).



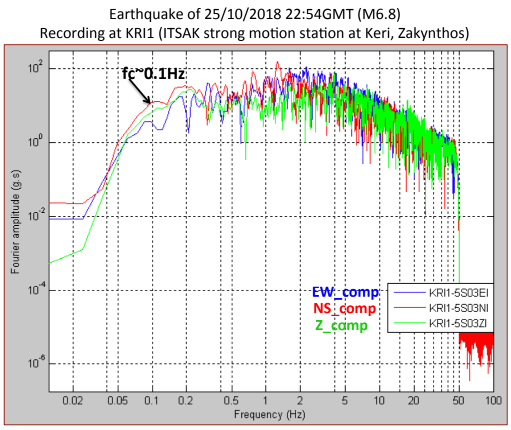
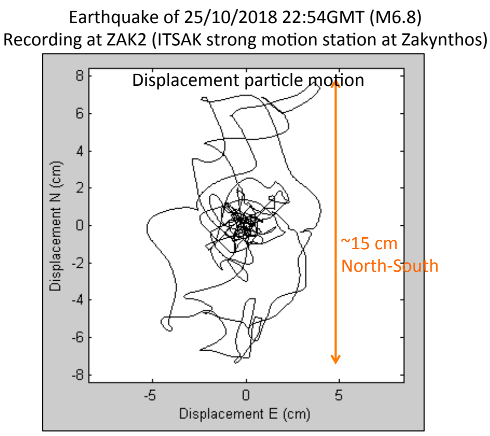


Figure 11. Fourier spectra and corresponding corner frequency (fc), for the 3 components of the acceleration time history in Zakynthos town (ZAK2, left) and Keri (KRI1, right).



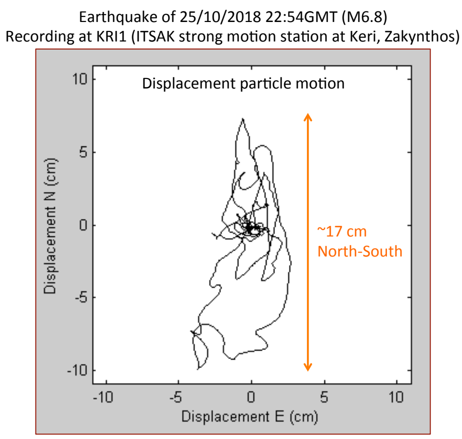


Figure 12. Displacement particle motion observed at Zakynthos town (ZAK2, left) and Keri (KRI1, right).

4.3 Elastic response spectra: Comparison between seismic codes and recordings

Code-defined and recordings-based elastic response spectra of the horizontal acceleration components (EW and NS) are compared in Figure 13 in absolute form, referring to ZAK2 (Figure 13-left) and KRI1 (Figure 13-right) stations. The corresponding spectra in normalized form are compared in Figure 14. The same results are plotted in Figure 15 with reference to the vertical acceleration component (UD) of the seismic motion. It is reiterated that the recordings of the M 6.8 Zakynthos earthquake (26/10/2018 – 01:54) are available at http://www.itsak.gr/news/news/155). Code-defined spectra were computed on the basis of the seismic hazard zone and soil category parameters reported in Table III. In Figure 13, the constant seismic design coefficients (being independent of the natural period of the structure) prescribed in the old Greek seismic codes of 1959 and 1985, are also plotted. These coefficients (noted with "ε" in the above Greek codes) were considered equal to ε=0.08, 0.12 και 0.16 for the island of Zakynthos, referring to progressively lower stiffness of the soil. However, an increased value (ε') equal to 0.137, 0.206 and 0.275, accordingly, is shown in Figure 13 which takes into account a safety factor (1.75), a 20% increase of the allowable stresses under seismic action and a coefficient (0.85) related to the multiple degrees of freedom of actual structures (Anagnostopoulos et al., 1987).

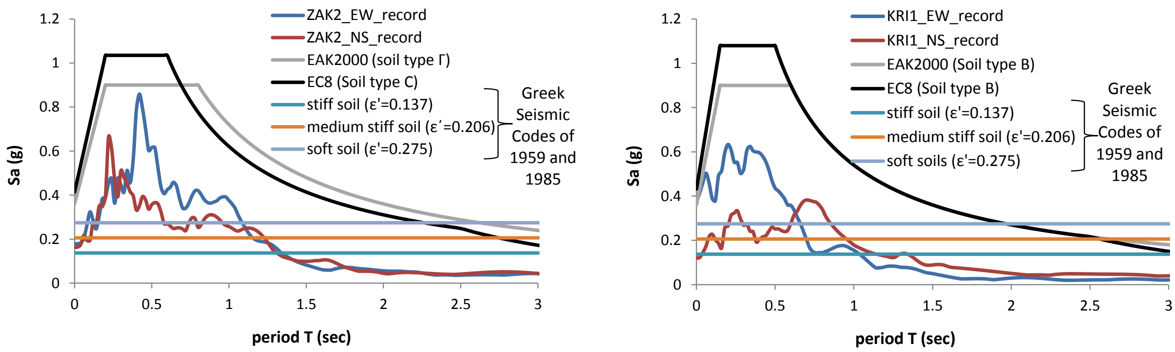


Figure 13: Comparison of absolute elastic response spectra between codes and recordings of the horizontal acceleration components (EW and NS) at ZAK2 (left) and KRI1 (right) stations.

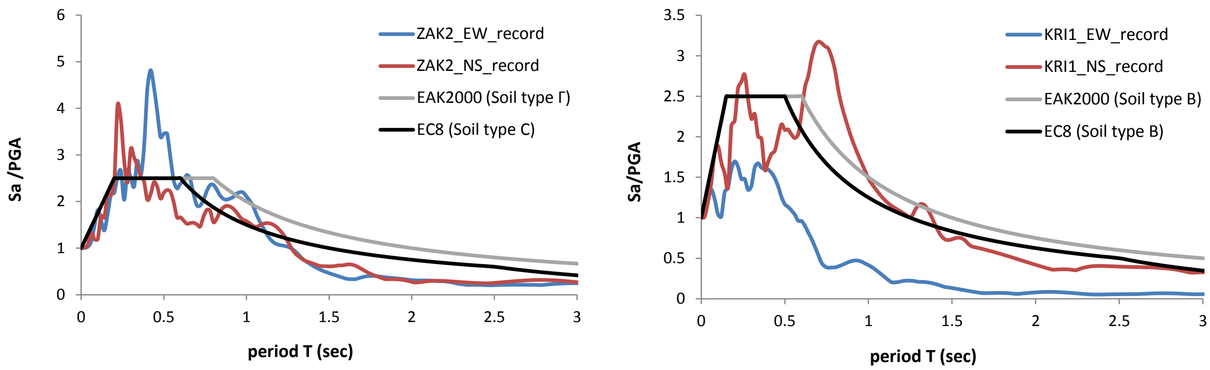


Figure 14: Comparison of normalized elastic response spectra between codes and recordings of the horizontal acceleration components (EW and NS) at ZAK2 (left) and KRI1 (right) stations.

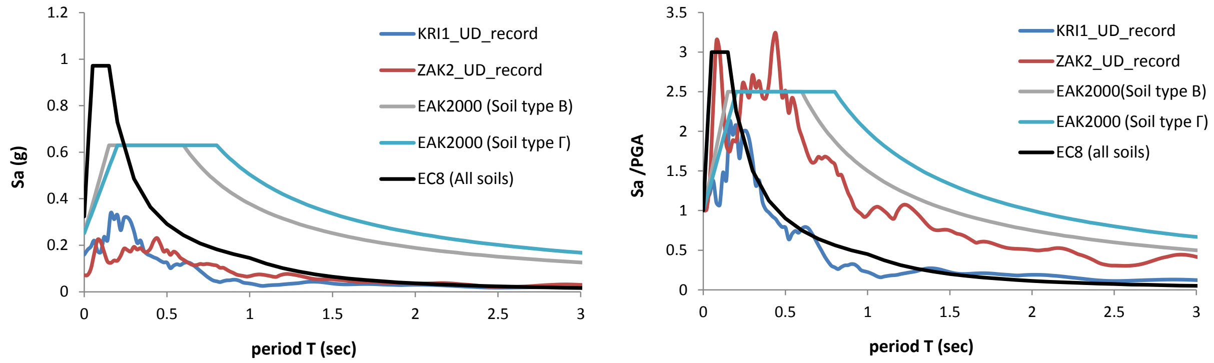


Figure 15: Comparison of absolute (left) and normalized (right) elastic response spectra between codes and recordings of the vertical acceleration component (UD) at ZAK2 and KRI1 stations.

It can be argued that structures designed according to the modern seismic codes (EC8 and EAK2000) sustained no damages given that design loads prescribed in the above codes are significantly higher than those induced by the earthquake motion (Figure 13). On the other hand, Figure 13 indicates also that typical R/C buildings in the city of Zakynthos with natural period in the range of 0.2sec to 1.0sec designed according to the 1959 Greek seismic code should have sustained light or severe damages depending on their vibrational characteristics. As a rule of thumb, the above range of structural periods refers to buildings with 2-3 (or more) floors.

With reference to the normalized acceleration response spectra of the horizontal components of motion, which may be viewed as an indication of local site effects, it can be observed that the code-defined amplification of seismic motion is generally higher than the recorded one for both ZAK2 and KRI1 stations. An obvious exception to the above trend is observed for the NS component of the KRI1 station record at a structural period close to 0.8sec (Figure 14).

With reference to the vertical component of motion, the absolute values of the code-defined spectra are significantly higher than the recorded ones (Figure 15). However, in normalized form, it is observed that ZAK2 station record is prescribed sufficiently by the EC8 spectrum only for structural periods lower than 0.2sec. For larger periods (T>0.2sec) the prediction of the EAK2000 spectrum is by far more representative compared to EC8.

5. EARTHQUAKE EFFECTS ON SOIL AND BUILT ENVIRONMENT

5.1 Port and quay walls failures

Extensive cracks parallel to the shoreline and failures of the quay walls in the form of permanent lateral displacement and tilting as well as settlement of the backfill were observed at the ports of Zakynthos (Pictures 1 and 2) and Ag. Sostis, following the **M** 6.8 earthquake of 26/10/2018. However, both ports remained functional after the earthquake.

It is worth noting that similar type of failures were observed at the ports of Lixouri (Picture 3a) and Argostoli (Picture 3b), following the Cephalonia earthquakes of January 26, 2014 (**M** 6.1) and February 3, 2014 (**M** 6.0), and at the port of Lefkas city, Ligia and Vasiliki in the island of Lefkas, following the **M**6.3 earthquake of August 14, 2003 (Pictures 4 and 5) and the port of Kos after the strong **M**6.7 earthquake (Picture 6).

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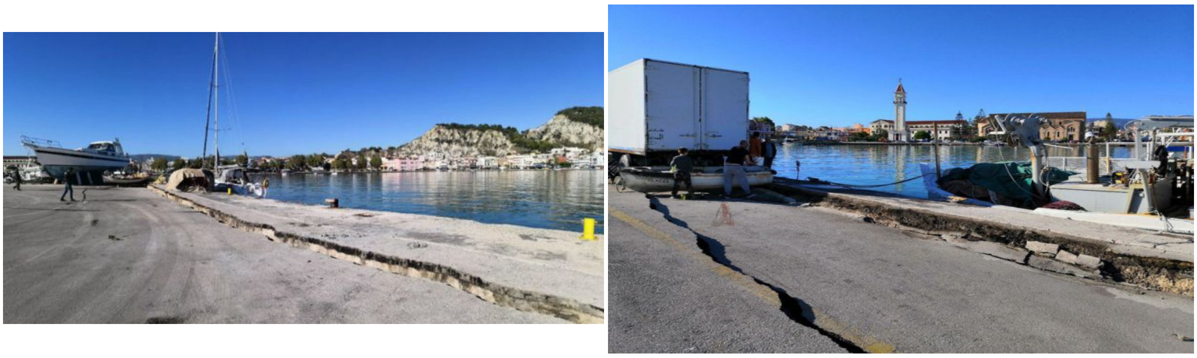
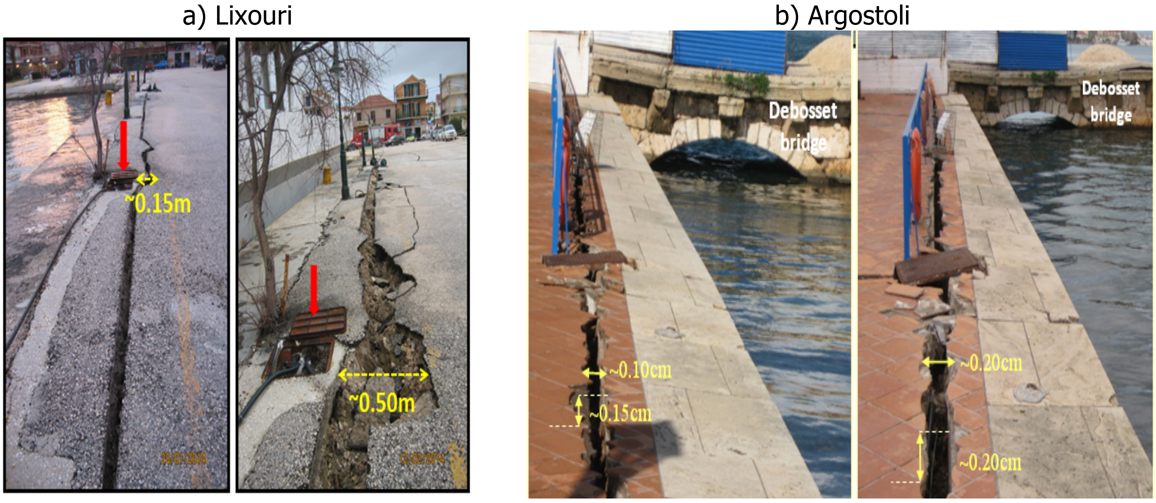


Picture 1. Extensive cracks and settlement of the backfill observed at the port of Zakynthos.

Picture 2. Lateral displacement and tilting of the quay walls at the port of Zakynthos

a) Lixouri

b) Argostoli



Picture 3. Observed failures at the ports of a) Lixouri and b) Argostoli following the Cephalonia earthquakes of January 26, 2014 (M6.1) and February 3, 2014 (M6.0)

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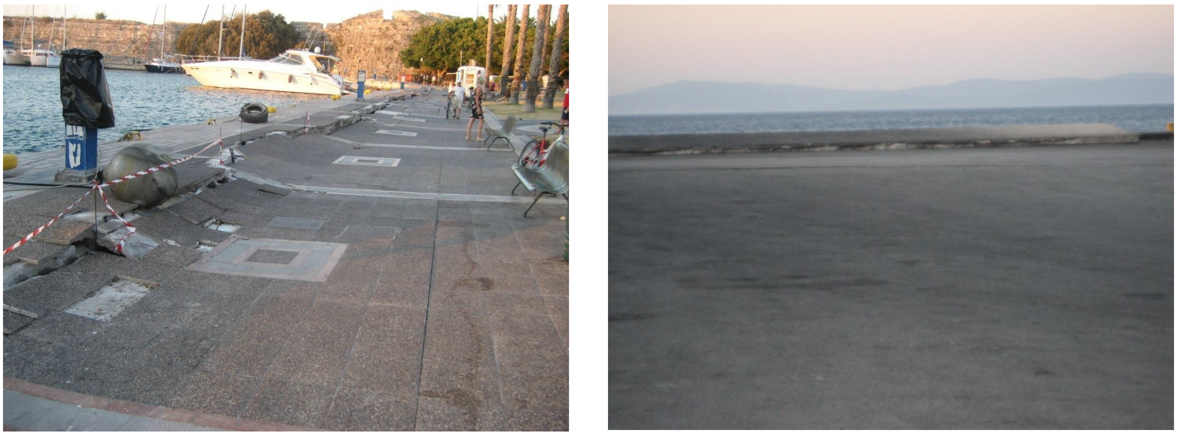
Picture 4. Earthquake-induced failures at the port of Lefkas, following the M6.3 earthquake of August 14, 2003.

Picture 5. Port and quay walls failures at Ligia and Vasiliki in the island of Lefkas, following the M6.3 earthquake of August 14, 2003

a) Kos – Port jetty

b) Kos – Port wharf



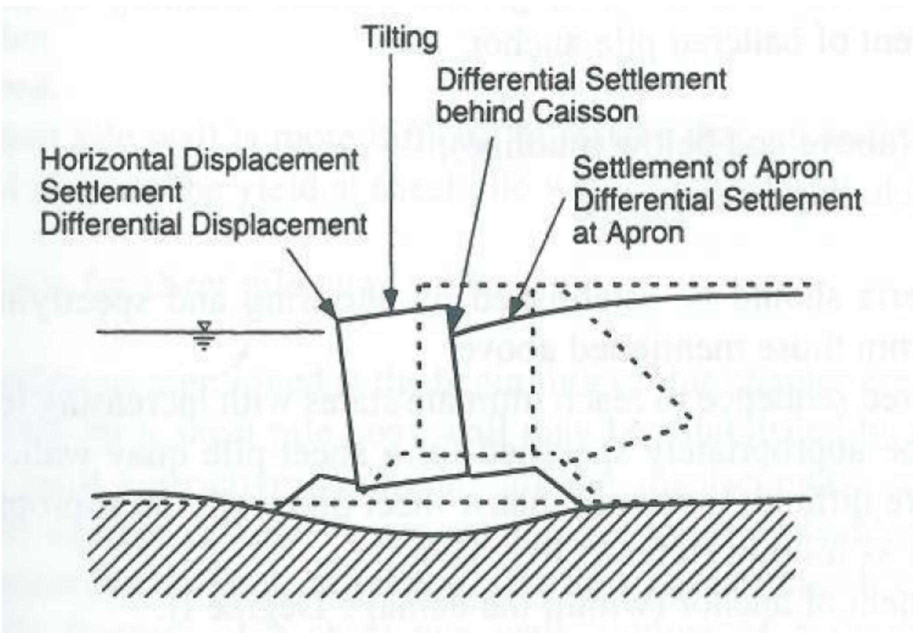
Picture 6. Earthquake-induced failures at the port of Kos, after the strong M6.7 earthquake.

The above earthquake-induced failures are in agreement with the mechanisms for specifying damage criteria for gravity quay walls shown in Picture 7. Besides the intensity of the earthquake shaking, the following parameters affect the seismic response of a gravity quay wall:

a) dimensions of the quay wall

b) bearing capacity of the foundation soil of the quay wall taking into account possible scouring effects due to sea currents.

c) type of backfill material. It is notes that in most of the aforementioned cases, earthquake-triggered liquefaction phenomena where observed.



Picture 7. Failure mechanisms for gravity quay walls.

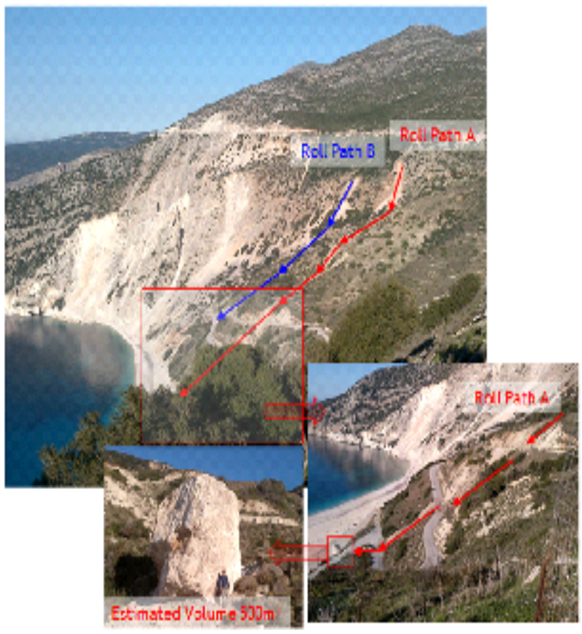
5.2 Rock slides and failures of stone masonry retaining walls

Several rock slides and slope failures were observed in the areas of Kryoneri and Panagoula of Zakynthos and in the shoreline of "Mizithres" close to Keri (Figure 8), including detachment of large blocks in some cases. Similar rock slope-type failure of a sandy marl escarpment was observed in the Xi area shoreline (Picture 9a) while important shallow disaggregated slides with debris flow occurred in the Myrtos Bay of Cephalonia (Picture 9b), following the destructive earthquakes in 2014.

Failures of stone masonry retaining walls were also reported (Picture 10). Such out-of-plane failures or even total collapses was also typically recorded for the above type of retaining walls following previous strong earthquakes (Cephalonia 2014, Lefkas 2015) at the Ionian Islands (Picture 11).

Picture 8. Landslide phenomena in the shoreline of "Mizithres" close to Keri (https://www.imerazante.gr/2018/10/28/185051)

(a)



(b)

Picture 9.(a) Landslides of sandy marls in the shoreline of Xi and (b) Detachment of limestone rocks along Mirtos bay after the Cephalonia earthquakes (26/01/2104 και 03/02/2014).

Picture 10. Collapse of a stone retaining wall following Zakynthos earthquake (Source: https://www.cnn.gr)

Picture 11. Typical failure types of stone retaining walls recorded after the Lefkas, 2015 (left) and Cephalonia, 2014 (right) earthquakes

5.3 Damage to built environment due to the 26/10/18 Zakynthos Earthquake

After the strong earthquake of 26/10/2018, the observed damage was limited to quay wall permanent lateral displacement at the Port and some plaster detachments at churches and traditional buildings. However, during the subsequent aftershock sequence, some damage to the infill walls of buildings was also observed.

The assessment of the structural condition of the buildings started on the very same day from the Department for Natural Disasters (DAEFK) of the Greek Ministry of Infrastructure and Transport. Damage was observed to a substantial number of buildings, and, according to gathered information, the most serious cases were for buildings in the areas of Kalamaki, Laganas, Lithakia, Keri, Machairado and Lagopodo. Out of the 250 inspected buildings, 120 were deemed as uninhabitable, according to the classification adopted by DAEFK, which includes the "yellow" and "red" categories of the internationally widely used post-earthquake structural assessment methodology.

Inspections to schools certified their immediate usability, except for two statically independent classrooms in corresponding school complexes (Elementary school at Pantokratoras and kindergarten at Ampelokipoi), in which repairs have to be made, without need for disruption of the operation of the remaining school infrastructure.

Traditional buildings built according to the local seismic provisions of 1953 presented some serious damage mainly to secondary structural elements (Pictures 12, 13). Among these, worth mentioning is the Castle-Monastery at the Strofathes island, due to its cultural importance (Picture 14).

Picture 12. Traditional building at Zakynthos town

Picture 13. Observed damage at Zakynthos town

6. CONCLUSIONS

The M6.8 earthquake of October 26, 2018, which took place in the sea area SSW of Zakynthos island, was caused by a reverse thrust, NW-SE fault (Papazachos and Papazachou 2003). This fault is related to recurring destructive earthquake events at Zakynthos island and its nearby areas.

The national strong motion network maintained by ITSAK (research unit of EPPO), recorded a peak ground horizontal acceleration (PGA) at Keri station of approximately 0.36g, equal to the design ground acceleration provided by the Greek National Seismic Code (EAK), as well as the National Annex of EC8 for the Seismic Hazard Zone III , which comprises the island of Zakynthos. At the station in the town of Zakynthos the corresponding recorded value was 0.17g. The peak ground horizontal velocity (PGV) in both stations was of the order of 17 cm/sec, despite the difference in the corresponding PGA values. The strong-motion duration was 15sec at Keri station and almost double (30sec) at Zakynthos station. The observed differences in the aforementioned parameters are related to the different distance of the two stations from the source, but mainly to the different soil conditions. The corner frequency (fc), estimated through the analysis of the corresponding amplitude Fourier spectra, was around 0.1Hz, a value expected for an earthquake of such a magnitude. Finally, the particle motion analysis shows as primary the N-S direction, with a peak-to-peak displacement of approximately 17cm.

Picture 14. Observed damage at the Castle-Monastery at Strofathes island

From a comparison of the seismic code design provisions which were applied throughout the years (1959-today) for the structures at Zakynthos island with the recorded motions of the 26/10/2018 event, an a priori evaluation leads to an expectation of damage to be mostly observed to 2-3 (or more) storey buildings constructed according to the 1959 and 1985 seismic codes. However, the actually observed damage was mainly related to failures of infill walls and secondary structural elements, a fact which can be attributed due to the overstrength provided by the infill walls (which typically are not taken into account in the design process), as well as to local good construction practices and workmanship, developed through the years due to the high seismicity of the area. Traditional buildings constructed according to special seismic provisions established for the Zakynthos area after the 1953 destructive earthquake (and before the establishment of the 1959 first National Seismic Code), presented some serious failures mainly at secondary structural elements.

Damage/failures in the form of ruptures along the jetties, as well as displacement and rotation of quay walls (together with a subsidence of the backfill material) were observed in the ports of Zakynthos and Agios Sostis, without, however, causing disruption to the operation of the ports. The general image of the response of such type of structures at Zakynthos, as well as also in previous earthquake events (e.g. at Lixouri, Argostoli, Lefkada and Kos) conforms to the observed failure mechanism of gravity quay walls to strong earthquake excitations. The degree of damage of gravity quay walls is related to the intensity of the seismic excitation, their overall dimensions, the bearing capacity of the foundation soil at their base, as well as the type and properties of the backfill soil materials.

The observed failures to natural and man-made earth embankments, as well as to masonry retaining walls were rather expected, since they are typically observed after almost each significant earthquake, even in cases with smaller PGAs than the 28/10/2018 event. These (mostly local) failures can be attributed to the fact that in many cases the weathered surface layer of the –mainly of limestone composition- sedimentary rocks is in a limit equilibrium state, and the slightest excitation can lead to the dislodgement and slipping of the materials of the weathered surface layer.

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