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AGU FALL MEETING

The October 11, 1918 Mona Passage tsunami modeled using new submarine landslide evidence

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1. Abstract

The October 11, 1918 ML 7.5 earthquake in the Mona Passage betweeen Hispaniola and Puerto Rico generated a local tsunami that claimed approximately 100 lives along the western coast of Puerto Rico. The area affected by this tsunami is now many-fold more populated. Although the exact cause of the tsunami is still unclear, newly-acquired high-resolution bathymetry and seismic reflection lines in the Mona Passage show a fresh submarine landslide 12 km northwest of Rincón in northwestern Puerto Rico and in the vicinity of the earthquake epicenter determined by Reid and Taber (1919). The landslide area is approximately 76 km^2 and probably displaced a total volume of 10 km^3. The landslide's head scarp is at a water depth of 1.2 km, with the debris flow extending down to a water depth of 4.5 km. Submarine telegraph cables were reported cut by a landslide in this area following the earthquake, suggesting further that the landslide was the result of the October 11, 1918 earthquake. On the other hand, fresh scarps were not observed at the previously suggested source of the 1918 tsunami, a normal fault along the east side of Mona Rift (Mercado and McCann, 1998), suggesting that it was not active recently. The fault escarpment along Desecheo Ridge and our landslide appear, on the other hand, to be rather fresh. The epicenter of Doser et al. (2005) is located neither near the landslide location nor the postulated Mona Rift eastern fault, but 30-40 km to the southwest where no surface rupture was identified in our data. Using the extended, weakly non-linear hydrodynamic equations implemented in the program COULWAVE (Lynett and Liu, 2002), we modeled the tsunami as generated by a landslide with a finite duration and with the observed dimensions and location. Marigrams (time series of sea level) were calculated at locations near to reported locations of runup. The marigrams show a leading depression wave followed by a maximum positive amplitude in agreement with the reported polarity, relative amplitudes, and arrival times. Our results suggest this newly-identified landslide, which was likely triggered by the 1918 earthquake, was the probable cause of the October 11, 1918 tsunami and not the earthquake itself. Results from this study should be useful to help discern possible tsunami sources of other case studies in which their sources are still poorly constrained.

2. Historical Evidence

Reid and Taber's (1919) survey describes the damages caused by both the earthquake and the tsunami. Of particular interest is the fact that as a result of the earthquake two ***submarine telegraph cables*** were ruptured. The cause of the rupture was documented to be the result of landslides. Below are excerpts from Reid and Taber's paper, where they describe the damage to submarine cables.

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THE PORTO RICO EARTHQUAKES OF OCTOBER-NOVEMBER, 1918.

By Harry Fielding Reid and Stephen Taber

Effects of the Earthquake on Submarine Cables

The cable of the West India and Panama Telegraph Company, connecting San Juan with Kingston, Jamaica, and the cable of the Compagnie Française des Cables Télégraphiques, from St. Thomas to Puerto Plata, Santo Domingo, were both broken at several places during the earthquake of October 11th. All of these breaks were within the area bounded by the parallels 18° 25′ and 18° 35′ north and the meridians 67° 15′ and 67° 30′ west. The cable of the French company between San Juan and Mayagüez, which runs closer inshore, was not affected.

the other cable, writes: "At the first rupture, the cable itself was not broken, but it would seem that it had been crushed by a very heavy landslide, for it was here found buried for two or three miles. The

above, and Captain Morrell states that "here again the cable was badly crushed and buried by a landslide, the break being due to the core having been spewed out and nipped by the outer sheathing wires."

In describing the appearance of the ruptured French cable, Captain Dulac of the cable-ship "Pouyer Quertier" states: "We picked up the ends of the first and third ruptures; at these two places our cable shows the same characteristic signs: the outer covering of jute was scraped off, and in several places the armature, which is of steel wire, was deformed and crushed."[5] Captain Morrell, in describing the damage to

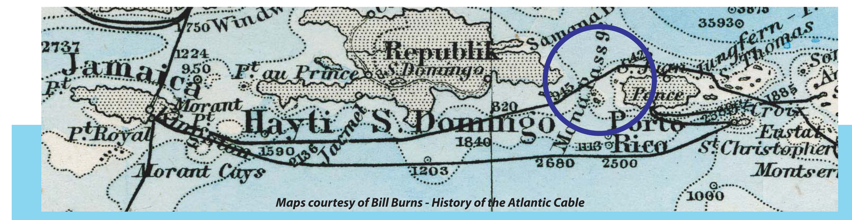


Figure 1: Map ca. 1900 showing approximate location of one of the submarine cables that connected Jamaica with Puerto Rico. The blue circle shows the location where the cable was ruptured. This map pre-dates the location of the other cable, hence not shown.

Reid and Taber also reported a prominent ***leading depression wave*** at all locations in western Puerto Rico with ***maximum wave amplitudes*** and first ***wave arrivals*** in northwest Puerto Rico. The locations they visited with their respective run-up (in decreasing order - going N-S): Punta Agujereada (5.5-6), Punta Borinquen (4.6), Punta Higüero (5.5), Aguadilla (>4), Mayagüez (1.1-1.5), Mona Island (4), and Boquerón (1.1) (see Figure 6 for locations).

3. Previous Suggestions for the Origin of the Tsunami

Mercado and McCann (1998) went back to the archive of available Mona Passage seismic reflection lines and upon re-interpretation they identified eight presumed active faults in the Mona Rift and chose the Mona Canyon fault, a normal fault on the western wall of the rift, as the preferred source for the generation of the tsunami.

Although their modeling results showed agreement of wave arrivals with observations, it did not yield the observed leading depression wave, suggesting a correct location for the source, but not for the mehanism.

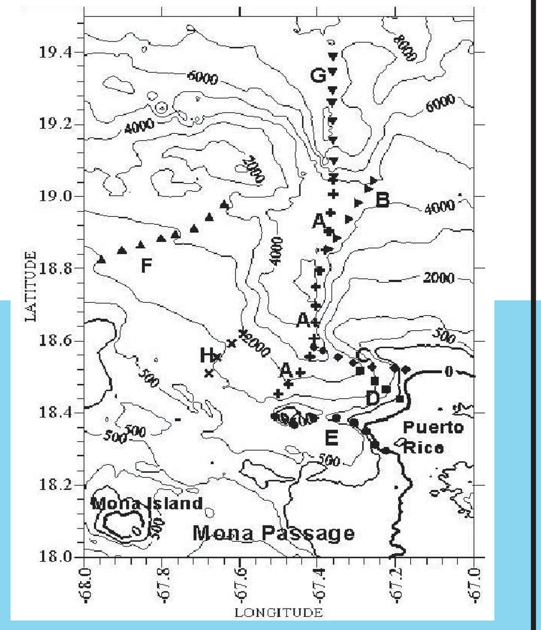


Figure 2: Mercado and McCann (1998) Mona Rift faults. Fault A (with crosses) was used to generate their tsunami. The fault length they used is 66 km (in 4 segments) with total slip of 4 meters, and fault width of 25 km.

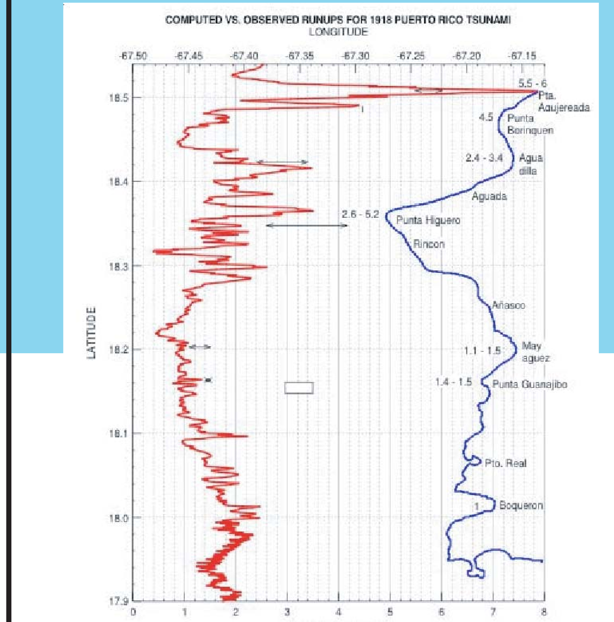


Figure 3: Results of maximum wave amplitudes (red curve) along the west coast of Puerto Rico (blue line). Notice their fault model overestimates wave amplitudes at the northwestern corner of Puerto Rico, while underestimating other locations south.

4. Geologic Evidence

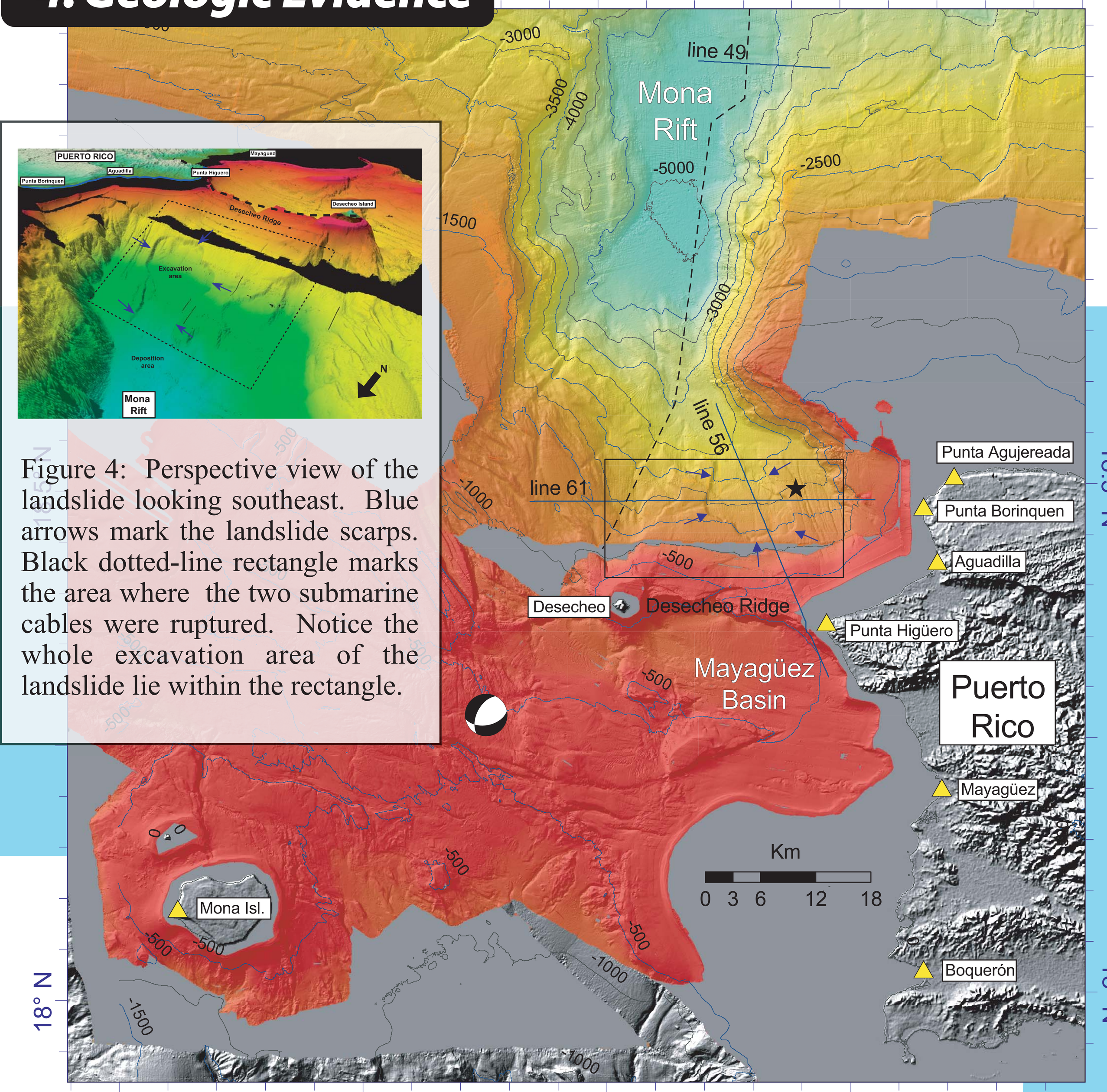


Figure 4: Perspective view of the landslide looking southeast. Blue arrows mark the landslide scarps. Black dotted-line rectangle marks the area where the two submarine cables were ruptured. Notice the whole excavation area of the landslide lie within the rectangle.

Figure 5 (below): Detail map of the landslide. Centered at 18.49° N, 67.35° W, the landslide's head scarp lies on the northward-tilted block of the Desecheo Ridge.

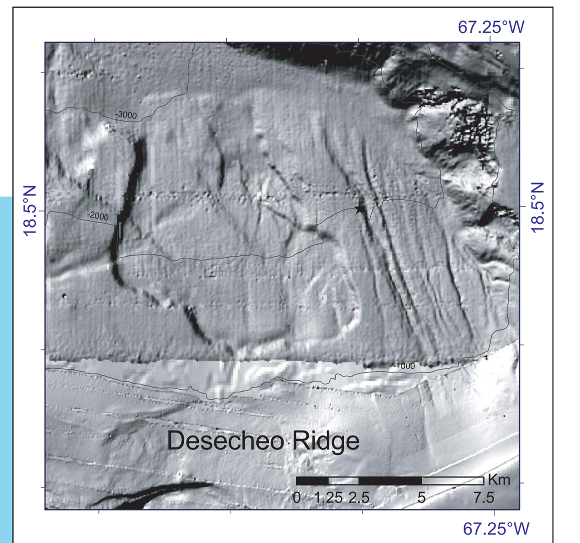
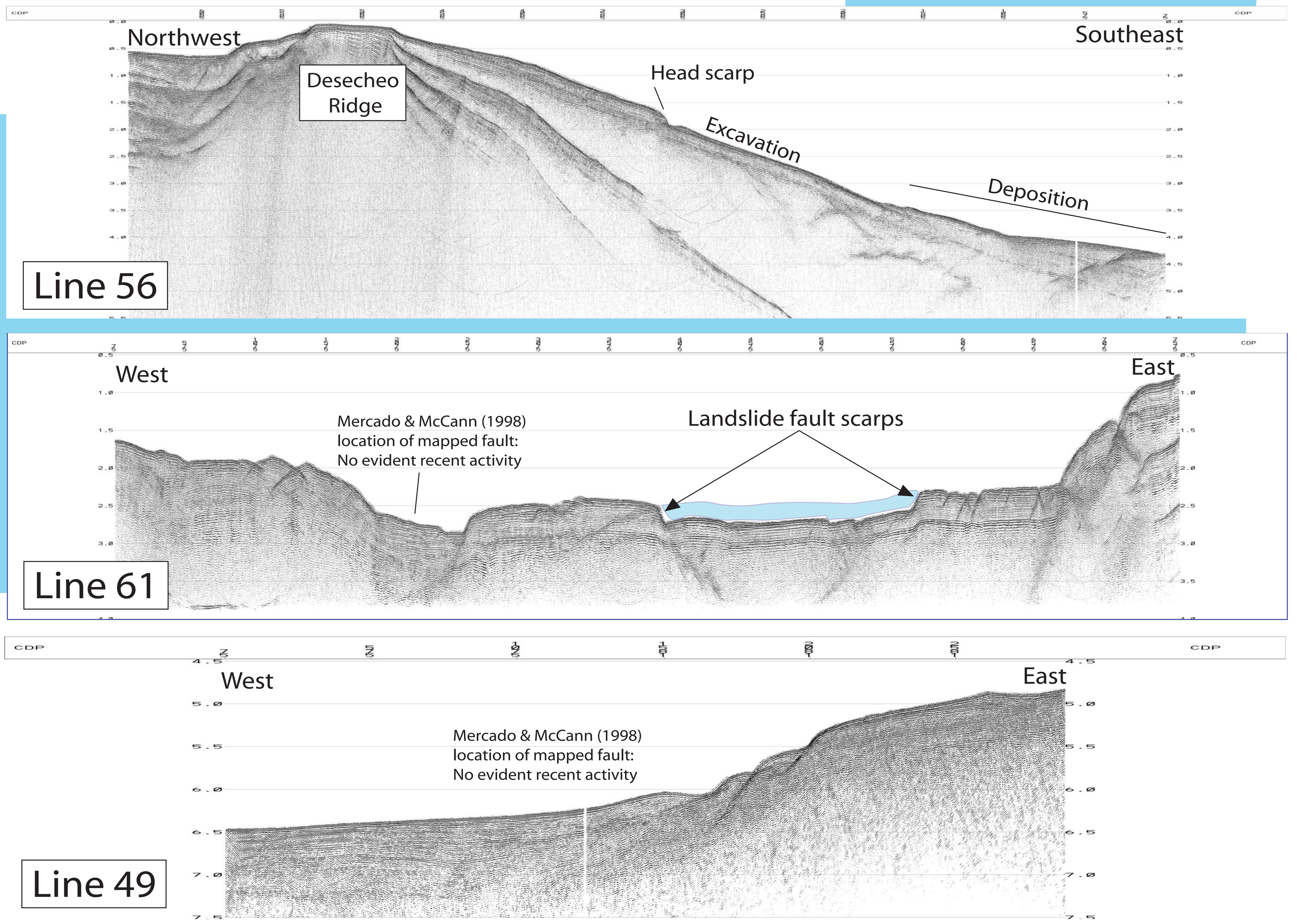


Figure 6 (left): Bathymetry of the Mona Passage showing the location of landslide with its fresh scarps (blue arrows) on the western, eastern and southern sides, excavation depths in agreement with seismic profiles (blue lines), and deposition of material north-northwest into the Mona Rift to a depth of 4,200 m. The area where the submarine cables suffered damage is show with a black rectangle. Both the landslide and the epicenter of Reid and Taber (black star) lie within the rectangular area. Doser et. al. (2005) epicenter (focal mechanism) is located 40 km SW of the slide, a location that shows no tsunami-producing geologic feature on our new multibeam bathymetry (see poster T13C-1475). Yellow triangles represent the locations where run-up values are available.

Figure 7: Seismic line 56 (oriented NW-SE) shows the profile of the landslide, where the fresh and steep scarp is easily identified. Similarly, seismic line 61 oriented E-W show the western and eastern limits of the landslide by steep-sided scarps, which have been used to obtain 130 m as an average for the amount of material removed in the vertical component. Seismic lines 49 and 61 does not show recent activity on Mercado and McCann's (1995) causative fault (black dashed line).



5. Tsunami Modeling

-Bathymetry grid: Resolution of 200 meters with dimensions 157 km x 134 km (similar to that on the Figure 6). The landslide's azimuth is ~350°, therefore we had to rotate the grid 10° counter clockwise to facilitate landslide computation parallel to the axis. Upon simulation, COULWAVE read the 200 m resolution grid and re-computed it depending on simulation parameters. Therefore, we either used 1600 m (for fast computations, such as those to obtain the results in Figure 9) or 400 m (for final simulations).

-Landslide dimensions: Taken from our bathymetry data, the excavation area is 8 km x 9 km with top and midpoint depths placed at 1200 m and 3000 m, respectively. According to the sediment deposition on our bathymetry data, the bottom of the slide was placed 16 km north of the head fault scarp at a depth of 4200 m. We used in our calculations a slide thickness of 155 m, in agreement with the 130 m obtained using our seismic profiles.

-Landslide duration and coefficient of friction: We performed 130 simulations varying these two parameters (see Figure 8). Preliminary runs using the coarse resolution (1.6 km) were based on a range of friction coefficients from 0.001 (silt/sand) to 0.006 (rippled sand) yielding a best landslide source duration of 325 seconds and better χ^2 values with larger friction coefficients. Therefore, we increased the range up to 0.06 to observe the resulting residuals. Ideal fits are close to unity, which in this case comforms to a friction coefficient of $4x10^{-2}$. However, since coefficients are related to water depth and higher values are associated to run-up, we opted for using a conservative value of $4x10^{-2}$ as the best option for our simulations. To test that our residuals computed using the coarse grid were correct, we computed two additional simulations with a higher resolution (400 m). The advantage of having a higher resolution results in more precise values, hence slighly higher residuals. However, the overall trend remains the same.

-What was the most likely landslide duration?

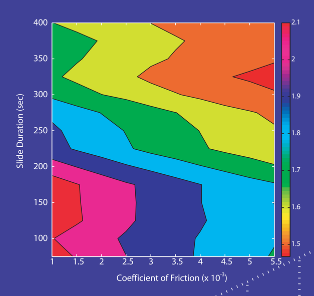
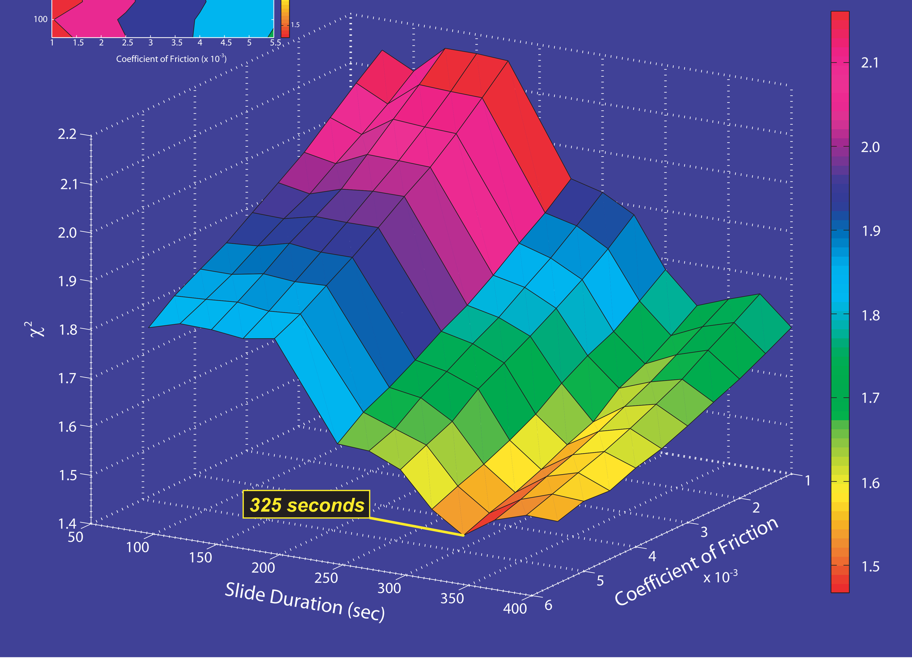


Figure 8: Chi square (χ^2) test revealed a landslide duration of 325 seconds was preffered at all coefficients of friction from 0.001 to 0.006. Figure to the left is the contoured 2D version of the Figure below.



-Which coefficient of friction fits better?

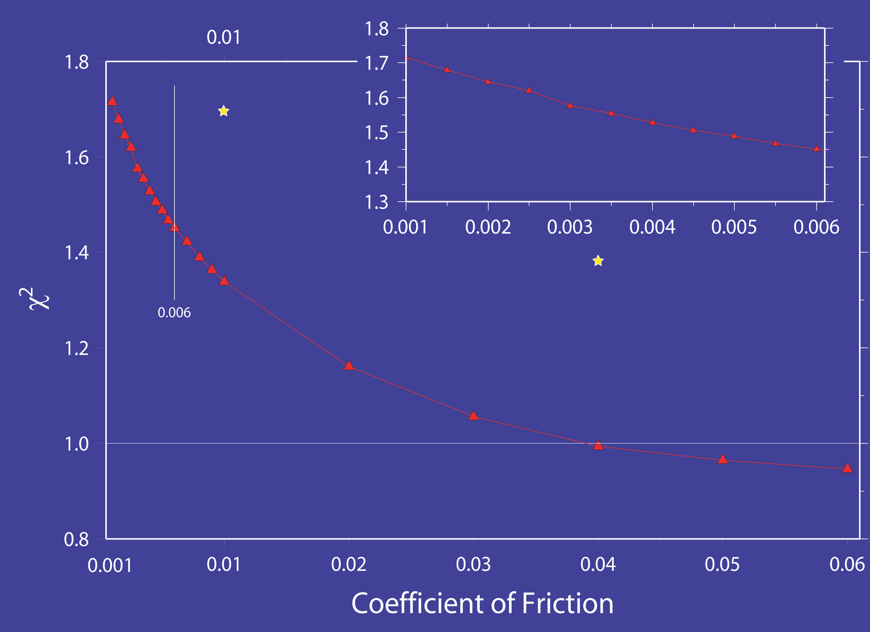


Figure 9: Red triangles show χ^2 values as a function of friction coefficient for the optimized slide duration of 325 seconds using a grid resolution of 1.6 km. Two additional simulations with a grid resolution of 400 m are shown with the yellow stars. According to this test, $4x10^{-2}$ shows the best fit, however, we opted for a more conservative value of $1x10^{-2}$ for our final simulations.

6. Results

We found the best combination of parameters that fit the observations consist of: Coefficient of Friction = 0.01; Landslide duration of 325 sec; Slide thickness of 155 meters. Using these parameters we produce maximum wave amplitudes, arrival times and polarities at 6 locations in western Puerto Rico and in Mona Island. The estimated slide duration yields a slide velocity of 27 m/sec, in agreement with suggested values.

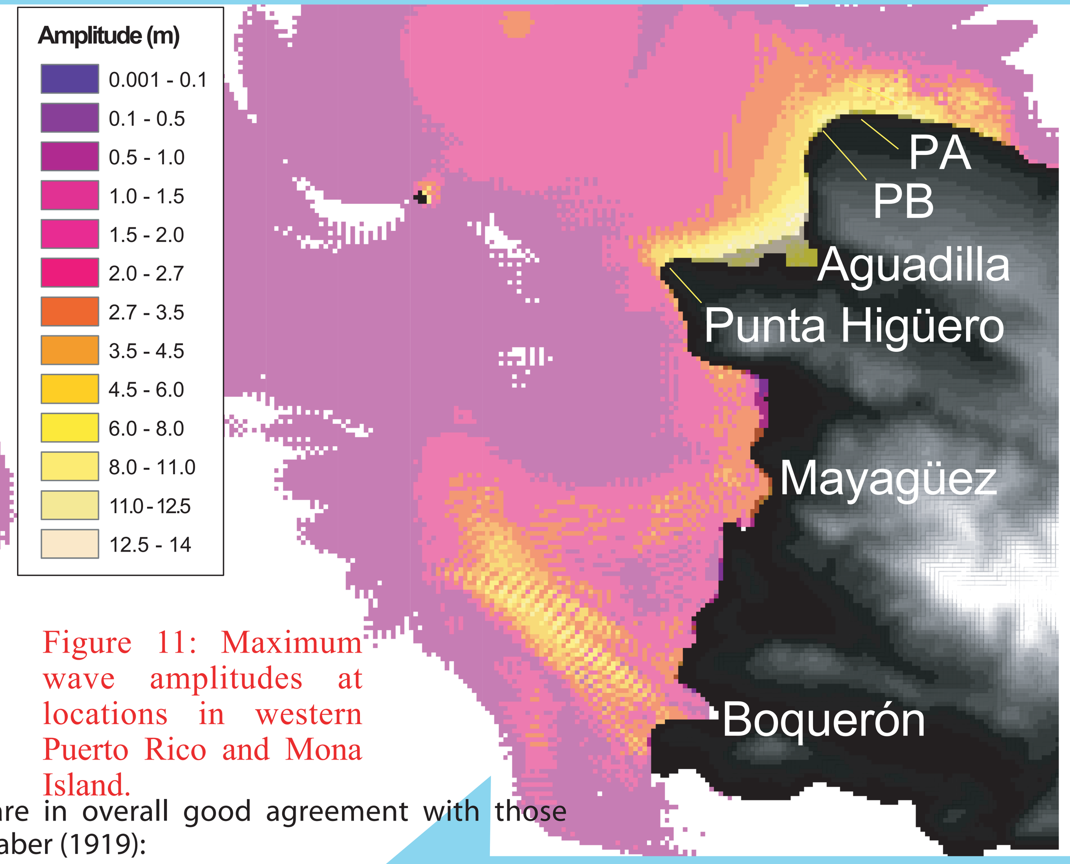


Figure 11: Maximum wave amplitudes at locations in western Puerto Rico and Mona Island.

Our model yields results that are in overall good agreement with those observations published in Reid & Taber (1919):

1) leading depression predicted at all sites
2) arrival times within the specified range
3) maximum wave run-up

Although the model fits well 3 out of the 7 sites (Boquerón, Mona and Punta Higüero), sites in the northwestern corner (Punta Borinquen and Punta Agujereada) and Mayagüez are slightly overestimated. Aguadilla is the worst fit in our data, however, we find unlikely observed values would range that low given that waves are naturally focused on that corner. In the other hand, the existence of high cliffs in northwest Puerto Rico may have prevented wave amplitudes with values computed here to be observed.

Our results also agree with observed geological evidence. Using a slide thickness of 155 m and a slide width of 9 km yields a total volume displaced of 8.8 km^3, which is in good agreement with the estimated value of 10 km^3.

Location	Observed			Computed	
	Run-Up (m)	Inundation (m)	Arrival time (min)	Run-Up (m)	Arrival time (min)
Punta Agujereada	5.5-6	‡	No Data	10.67	7
Punta Borinquen	4.6	100	"immediately"*	8.97	5
Aguadilla	> 4.0	45-75	5-6	12.83	7
Punta Higüero	5.5	No Data	~ 2†	6.23	5
Mayagüez	1.1-1.5	No Data	25-30	2.70	18
Sardinera, Mona	> 4.0	No Data	No Data	3.42	18
Boquerón	1.1	No Data	45	1.65	44

* According to the lighthouse keeper the arrival of the initial wave was "immediately" after the earthquake.
‡ A cliff of ~100-120 meters high prevented flooding.
† Arrival time of first depression is unknown. However, here was reported the time between maximum depression and arrival of elevated wave.

Table 1: Summary of observed and computed values. Observed values taken from the survey of Reid & Taber (1919). Computed values were obtained using the preffered parameters discussed in Section 5.

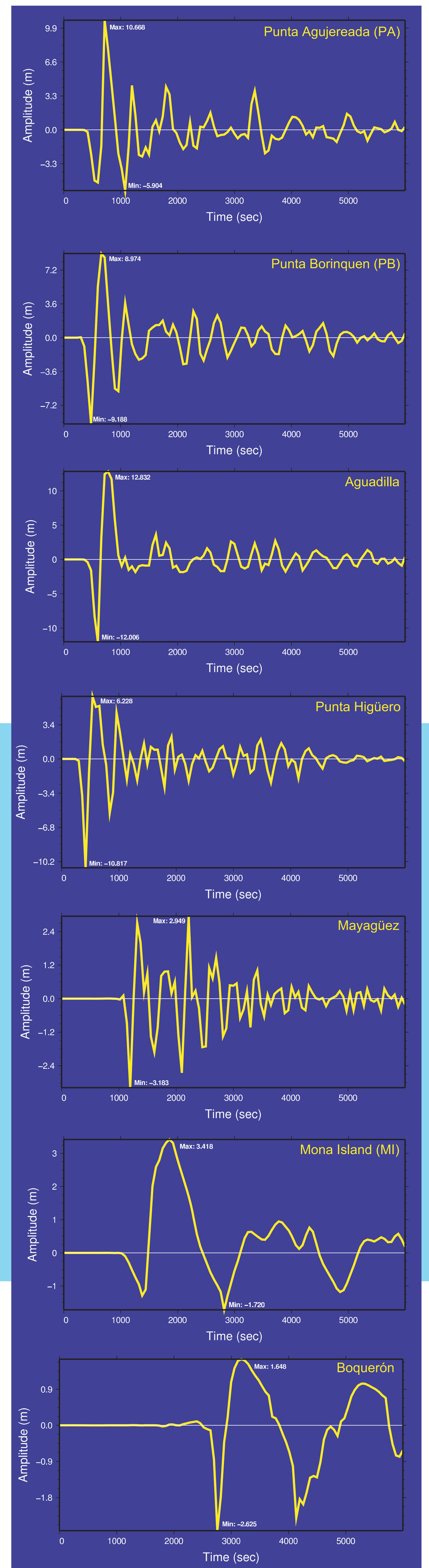


Figure 10: Time histories of sea surface elevations. Notice the leading depression wave at all sites.

6. Conclusions

The October 11, 1918 Mona Passage earthquake triggered a tsunami that affected the western coast of Puerto Rico. The cause of the tsunami was poorly known and was suggested to be due to a normal fault on the Mona Rift. However, we have identified a submarine landslide 15 km off the northwestern coast of Puerto Rico using new available multibeam bathymetry and seismic reflection profiles. Based on these data we postulate the landslide was responsible for the tsunami genesis. Using these new available data we identified the location and dimensions of the slide. A strong evidence supporting this idea is the documented rupture of submarine telegraph cables by landslides.

Using the dimensions of the slide, we modeled the tsunami using COULWAVE and we found:
1) Slide location produces the expected arrival times.
2) Slide geometry produces the expected leading depression wave.
3) The landslide most probable had a duration of 325 seconds, which results in a slide velocity of 27 m/sec.
4) Using a maximum slide thickness of 155 m yields acceptable amplitudes.
5) A total displaced volume of 8.8 km^3, a value that is in agreement with estimates using our bathymetry and seismic profile data.

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