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The Pacific Tsunamigenic Earthquakes in the Early 2024

G. I. Dolgikh[a], * **and S. G. Dolgikh**[a], **

[a] *Ilichev Pacific Oceanological Institute, Far East Branch, Russian Academy of Sciences, ul. Baltiiskaya 43, Vladivostok, 690041 Russia*

**e-mail: dolgikh@poi.dvo.ru*

***e-mail: sdolgikh@poi.dvo.ru*

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Abstract—We are using data for two tsunamigenic earthquakes to develop a procedure for determining the displacement of sea bottom giving rise to tsunamis. We show that, assuming an average geometrical spreading factor for strain anomalies recorded by a laser strainmeter worldwide, we can find an approximate estimate of sea bottom displacement at a tsunamigenic site. There are more accurate spreading factors for each region where tsunamis have been generated; these can be estimated experimentally to be used for more accurate determination of sea bottom displacements.

Keywords: earthquake, strain anomaly, geometrical spreading factor, tsunami

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INTRODUCTION

Tsunami is one of the most catastrophic phenomena on Earth causing considerable losses to mankind. One characteristic example is the tsunami which occurred in the Indian Ocean on December 26, 2004 due to a great earthquake whose maximum magnitude was 9.3 (Stein and Okal, 2005), and whose death toll was about 300 thousand. Tsunamis constitute a threat for several regions of our planet, with those subject to the greatest hazard being Japan, Taiwan, and the Pacific coast of Russia, although the problem of detecting the time a tsunami will be produced seems to be solvable. The Japanese islands and adjacent marine areas contain various seismic stations, GPS stations, ocean bottom seismographs, and precision sea level meters. Nevertheless, the events of 2011 made more acute the problems arising in short term tsunami prediction.

At present, the traditional method of short term tsunami prediction is based on seismological information (earthquake magnitude, mainshock time, and epicenter location) (Wei et al., 2014). The magnitude of an earthquake in excess of a preset threshold value, which differs among different tsunamigenic zones, commonly prompts the authorities to issue a tsunami warning. This approach is based on a "magnitude-geography principle"; it is simple to use, gives low rates of failures-to-predict, but also yields false alarms. Most existing early tsunami warning systems are based on the seismological principle.

In recent years promise is shown by a "strain method for determining the occurrence time and magnitude of tsunamis" using sea bottom displacements at the tsunamigenic site that can be remotely recorded by laser strainmeters (Dolgikh and Dolgikh, 2021, 2023).

The strain method for determining the tsunami-generating potential of a submarine earthquake was tested using the catastrophic tsunamis generated by large earthquakes during the last twenty years. The presence of a strain step at the time of an earthquake provides evidence of a bottom displacement that is characteristic of tsunami generation. We have calculated attenuation coefficients of these displacements for all earthquakes considered. Using the coefficients based on laser strainmeter observations, one can not only find whether an earthquake in question is of the tsunamigenic type, but also determine the magnitude of the displacement at the earthquake location. Bearing in mind that these strain anomalies travel considerably faster than tsunami propagating in open ocean/sea, the strain method should be regarded as one of the more promising ones for determining the degree of tsunami hazard for a concrete earthquake.

Dolgikh and Dolgikh (2022) determined geometrical spreading for each tsunamigenic earthquake described in (Dolgikh and Dolgikh, 2021) using the relation

$$A = A_0 \frac{1(m)}{R^{\alpha}(m)},$$

where A is the displacement as recorded by a laser strainmeter, A_0 is the displacement recorded at the epicenter of the earthquake, R is the distance between

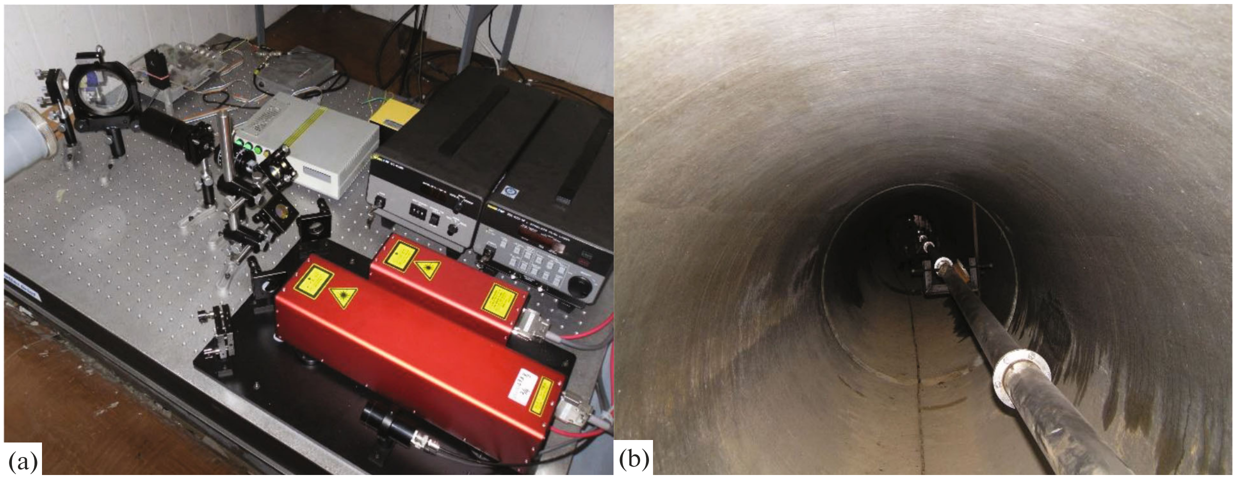

Fig. 1. A horizontal laser strainmeter with light path length 52.5 m. Central interference assembly of the laser strainmeter; (b) underground pipeline with a vacuumed pipe.

the site of the laser strainmeter and the epicenter, and α is geometrical spreading factor. It is 0.951 on average. Dolgikh and Dolgikh (2023) studied two earthquakes to find 0.941 and 0.952 for for the factor. Based on the data for all earthquakes described in (Dolgikh and Dolgikh, 2021, 2023), the average value of geometrical spreading factor would be 0.950.

This study is concerned with data for tsunamigenic earthquakes occurring in the Sea of Japan and off Taiwan; we are using these data to find sea bottom displacements for each earthquake and to get more accurate values of geometrical spreading factor.

THE LASER STRAINMETER

A laser strainmeter with unequal light paths and path lengths of 52.5 m was installed on Cape Schultz in the Sea of Japan at a depth of 5 m below the ground surface. It was oriented at an angle of 18° relative to the north–south line. Figure 1 shows a photograph of the central measuring interference assembly of the 52.5-meter laser strainmeter and an underground pipeline 1.5 m in diameter with a vacuumed pipe of stainless steel where a beam emitted by a helium–neon laser propagates between the interference assembly and a corner reflector. The central interference assembly is installed on a concrete block about 3.5 m high which is cemented to bedrock. The corner reflector is situated on a block about 1 m high which is firmly attached to a granite rock. All elements of the interferometer are underground at a depth of 5 m in good hydro- and thermo-isolated rooms. The room housing the central interference assembly was designed on the thermostat principle with a possibility of remote conditioning for the outer thermostat room, which is not in contact with the optics of the central interference assembly. The optical circuit of the laser strainmeter is designed on the scheme of the unequal-path Michelson interferometer whose length of the working (measuring) path is 52.5 m, which allows displacement measurements using the measuring path of the laser strainmeter to an accuracy of 0.01 nm. The linear working frequency range of this strainmeter is roughly between 0 and 100 Hz, while at higher frequencies the amplitude–frequency response function of the instrument follows a cosine function (Dolgikh, 2011). Recalling the length of the measuring path, we can assert that the laser strainmeter has a sensitivity equal to $\Delta l/l = 0.01\ \text{nm}/52.5\ \text{m} \approx 0.2 \times 10^{-12}$.

THE JAPANESE EARTHQUAKE

The first day of 2024 saw a large earthquake occurring in a seismic region of Japan, the northeastern termination of the Noto Peninsula. A total of over 20000 earthquakes have occurred in the region between May 2018 to December 2023, with more than 60 events having magnitudes above 4. The zone of seismic activity expanded in December 2020, and still more so in July 2021 (Hirose et al., 2024). The largest earthquake to have occurred in the region took place at 07:10:09 UTC January 1, 2024; its magnitude was 7.6. This was the largest earthquake to have occurred on the western coast of Japan for a period of over 100 years. After this event, the Japan Meteorological Agency (JMA) recorded over 140 smaller earthquakes, with one of these having magnitude 6.2. A tsunami alert was issued after the earthquake of January 1, 2024. The oceanic waves along the western coast of Japan reached heights of 1.2 m in some areas (Conroy, 2024). A tsunami alert was also issued for the Russian Far East; the waves in that region rose to heights of about 0.3 m. Short term tsunami forecasting is based on seismological information (epicenter location and earthquake magnitude) (Wei et al., 2014). Threshold magnitude values

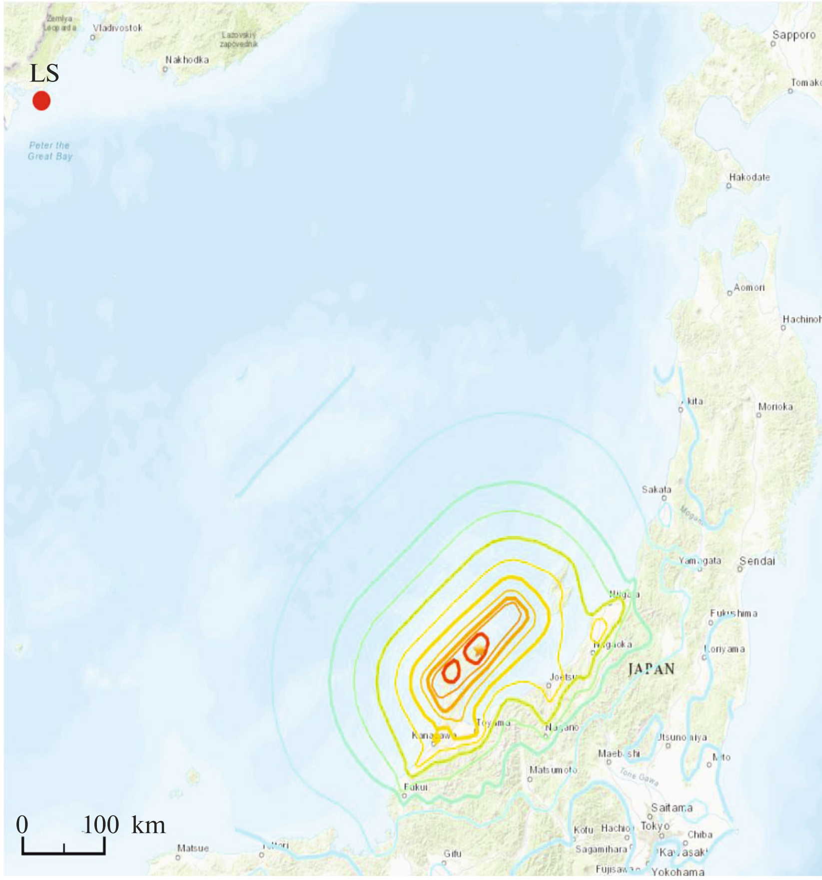

Fig. 2. The January 1, 2024 earthquake in the Sea of Japan. LS stands for *laser strainmeter*.

were established for different tsunamigenic zones, an exceedance resulting in the issue of a tsunami alert.

The records of the laser strainmeter showed first oscillations due to the earthquake at 07:12:05 UTC January 1, 2024. The epicenter was at the point whose coordinates were 37.487° N, 137.271° E, the depth of focus was 10 km (Fig. 2). The distance between the earthquake epicenter and the strainmeter site was about 770 km. The earthquake was also seen on records of a broadband seismometer that had been installed near the laser strainmeter. The signals reached both of these instruments in less than 2 min.

Figure 3 shows record fragments of the laser strainmeter and the broadband seismometer. Figure 3a shows a record fragment of the laser strainmeter lasting 137 min, while Fig. 3b displays an enlarged fragment of the laser interference strainmeter record at the time the earthquake was recorded, while Fig. 3c shows a fragment of the broadband seismometer record for the same time span. The vertical line in Fig. 3a marks the time instant when the earthquake started occurring. An analysis of the laser strainmeter record revealed a strain anomaly that is characteristic of tsunamigenic earthquakes (see Fig. 3a). This strain anomaly is absent on the record of the broadband seismometer. The magnitude of the anomaly was 13.5 μm.

The displacement of sea bottom at the site of tsunami origination was found from the relation quoted above. Recalling that the distance between the site of the laser strainmeter and the earthquake epicenter is about 770 km, the displacement on the record of the horizontal laser strainmeter is 13.5 μm, and the average geometrical spreading factor is 0.950, we find that the peak ground displacement at the epicenter was 5.3 m. The USGS site gives 6 m for the peak theoretical model displacement at the source [https://earthquake.usgs.gov/earthquakes]. The difference between the theoretical value based on laser strainmeter observations and the model displacement is due to the fact that we used the average geometrical spreading whose value varied between 0.923 and 0.974 as found by previous research (Dolgikh and Dolgikh, 2022), while the values for the Japanese Islands are in the range 0.941 to 0.952 (Dolgikh and Dolgikh, 2023). The average geometrical spreading can be adjusted for each region when there are many tsunamigenic earthquakes recorded by laser strainmeters. The spreading factor must be 0.959 in order to make the crustal displace-

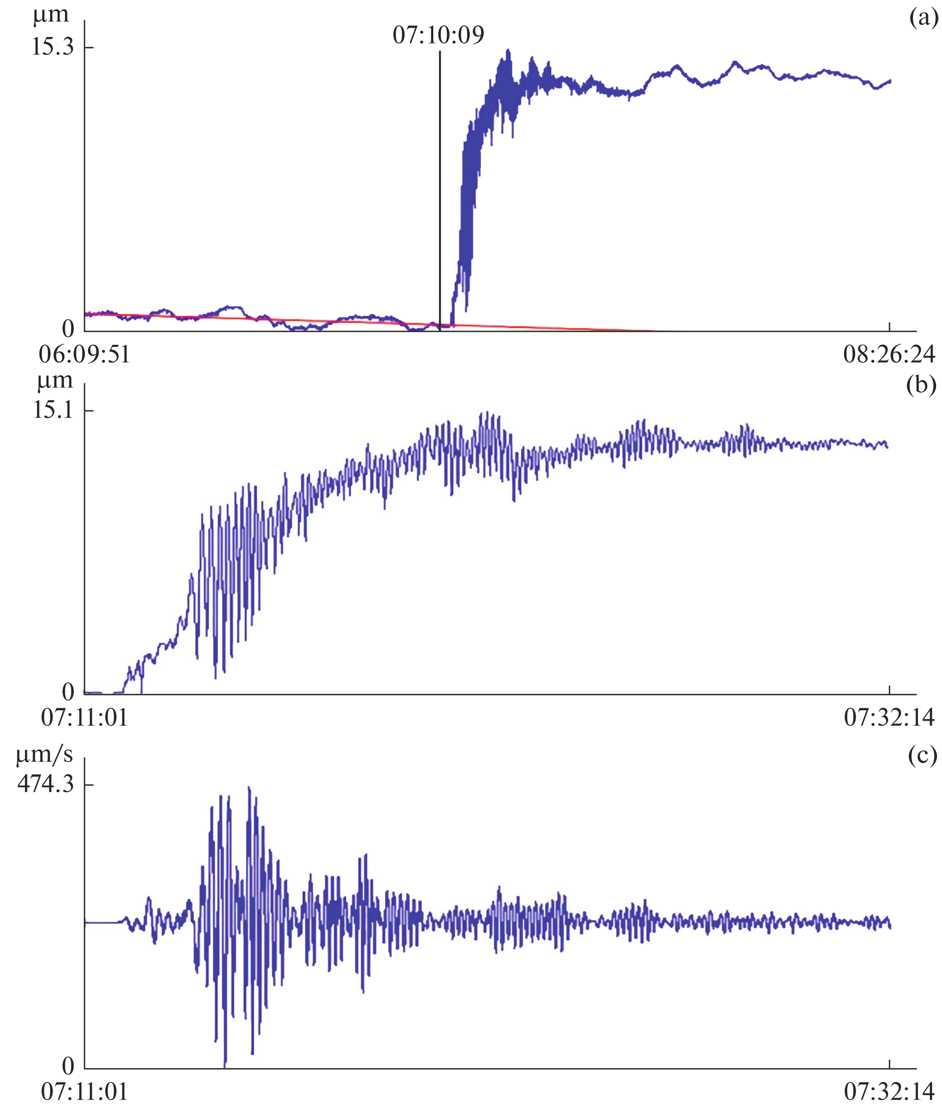

Fig. 3. The January 1, 2024 earthquake in the Sea of Japan as recorded by the laser strainmeter and by the broadband seismometer (UTC time). (a) a fragment of the laser strainmeter record lasting 137 min, (b) an enlarged fragment of the laser strainmeter record, (c) a fragment of the broadband seismometer record.

ment at the source resulting from our calculations coincide with the model calculation.

The strain anomaly took less than 2 min to reach the laser strainmeter site, while the small tsunami wave came to the Russian Far East coast much later. Since the wave was not large, it posed nearly no threat to human lives. Nevertheless, we can state that tsunami prevention measures can be more effective when based on laser strainmeter records.

THE TAIWAN EARTHQUAKE

A large earthquake occurred on Taiwan on April 2, 2024 at 23:58:11 (UTC); it was the largest for the last 25 years. The epicenter was at the point having the coordinates 23.819° N, 121.562° E and the depth of focus was 34.8 km (Fig. 4). The magnitude was 7.4. The epicenter was actually on land, but a tsunami alert predicting a height of 3 m was issued in Japan. Following that earthquake, more than 40 aftershocks have been recorded with magnitudes about 5. The largest occurred 12 min after the main shock, at 00:11:25 April 3, 2024. The epicenter was in a bay near Xincheng Township at a distance of 6 km from the shore, at the point with the coordinates 24.064° N, 121.672° E and the depth of focus 12.6 km. This earthquake was not followed by a tsunami alert as reported at the USGS site.

The Taiwan earthquake was recorded in the southern Russian Far East at the "Mys Shultsa" Marine Experimental Base of the Pacific oceanological Institute, Far East Branch, Russian Academy of Sciences.

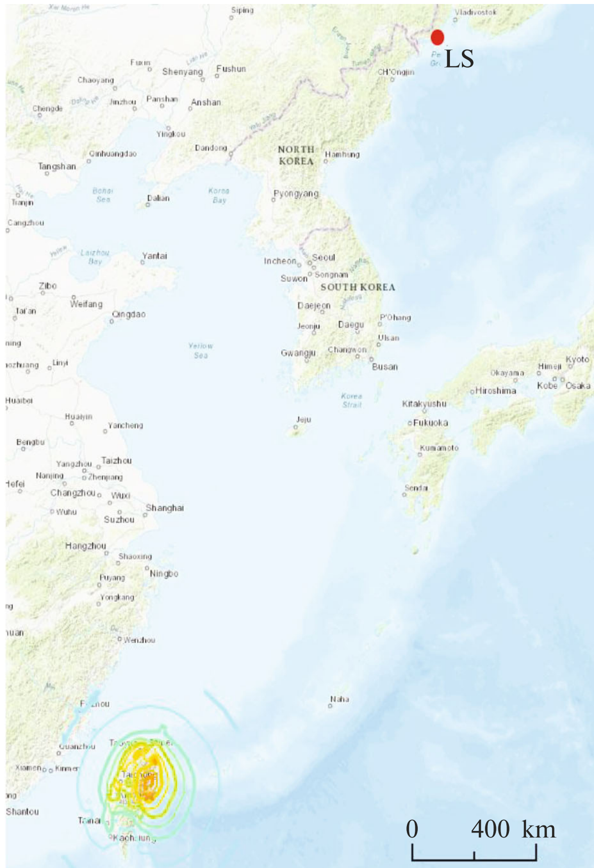

Fig. 4. The April 2, 2024 Taiwan earthquake. LS stands for *laser strainmeter*.

The distance between the epicenter of the first earthquake and the site of the laser strainmeter was about 2264 km. The time when the earthquake signal arrived to be recorded by the laser strainmeter was 00:08:14 on April 3, 2024; that is to say, the laser strainmeter recorded the earthquake about 10 min after its occurrence. Figure 5a shows a fragment of the laser strainmeter record lasting 70 min, while Fig. 5b shows an enlarged fragment of the earthquake record, and Fig. 5c displays a fragment of the broadband seismometer record for the same time span. The vertical line in Fig. 5a marks the time the earthquake began. The red line in Fig. 5a is a trend line which indicates how the record should have behaved, if no earthquake had been recorded. We can see that the record had deviated from the trend a few minutes before the earthquake was recorded. The record continued to move upward at the time when the oscillation of upper crustal layers arrived.

The next step was to use the expression described above to find the sea bottom displacement at the tsunami source, which is 1.32 m, when the geometrical spreading factor is assumed to be 0.951. The displacement is in good agreement with the values reported at the USGS site [https://earthquake.usgs.gov/earthquakes/].

CONCLUSIONS

We determined sea bottom displacement to be 1.32 m at the source of the April 2, 2024 Taiwan earthquake by a remote method using observations of a 52.5-meter laser strainmeter installed in the Russian Far East, as well as finding a sea bottom displacement of 5.3 m due to the Japanese earthquake. The use of these values for subsequent model calculations can help determine the wave heights of possible tsunamis arising from sea bottom displacements.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

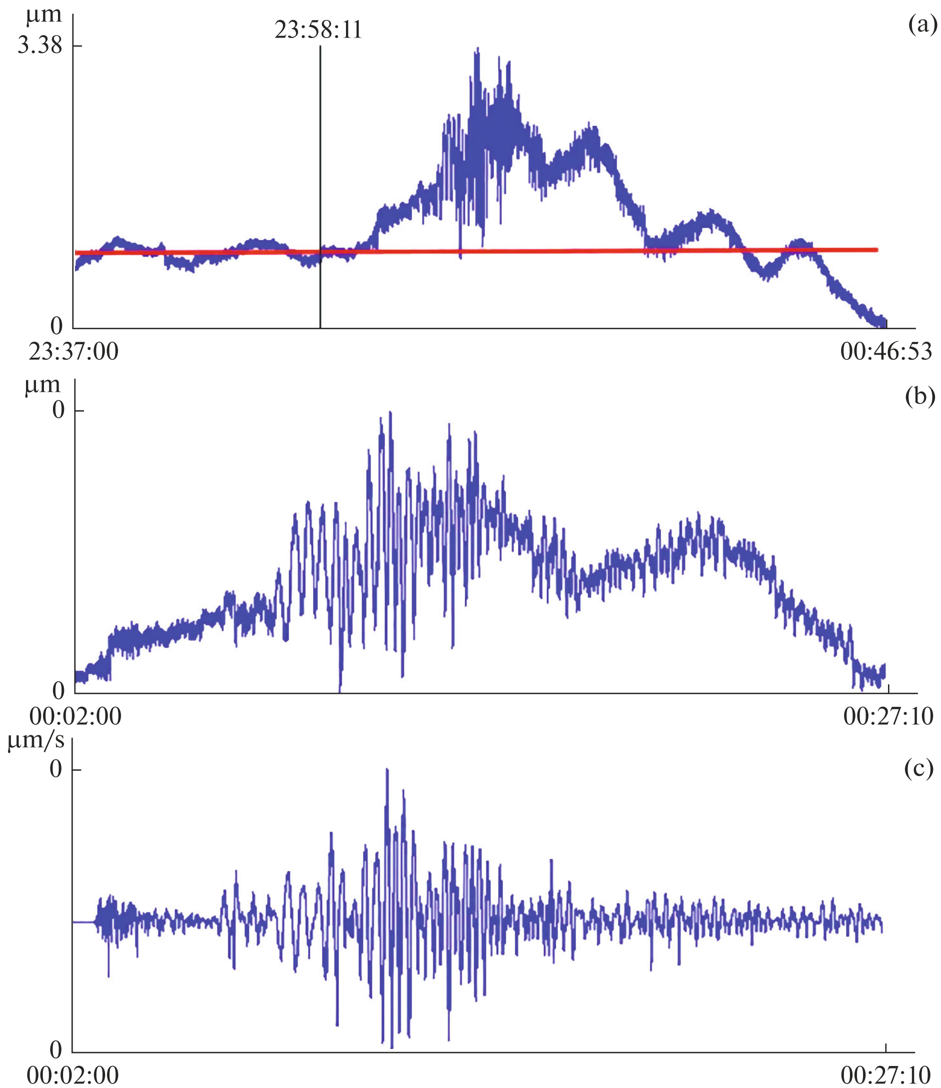

Fig. 5. The Taiwan earthquake on a record of the laser strainmeter (UTC time). (a) a fragment of the laser strainmeter record lasting 70 min, (b) an enlarged fragment of the earthquake record, (c) a fragment of the broadband seismometer record.

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