Analyzing Seismicity of the 2021 ML 4.9 Seogwipo Sea Earthquake in South Korea and Its Sequence by Using the Matched-Filter and the VEL/HYPOELLIPSE Methods

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Abstract: A moderate sized Seoqwipo earthquake (ML 4.9) occurred off-shore of southwest Jeju island, the largest volcanic island of the Republic of Korea, in December 2021 and it followed by several aftershocks. In the study area there were a few M3 events before the mainshock of ML 4.9 earthquake, and this was the first M4 class earthquake in the surrounding area since 1905. This event produced a maximum intensity V near Jeju island and III on the inland. To distinguish the seismicity and properties of the study area, we searched for more aftershocks within ten days after the msinshock with the Matched-Filter method. Then we detected about three times more events than the KMA (Korea Meteorological Administration) catalogue. The 1-D velocity model has not been discovered yet for this area, so we used the VELELLIPSE location method for more accurate hypocentral parameters. This method is the combination of HYPOELLIPSE, one of the hypocentral inversion methods, and the velocity updating algorithm. After relocating the Seogwipo earthquake sequence, we found that the aftershocks distributed along the NE-SW direction which was corresponding to the strike of the mainshock according to the focal mechanism solution.

Keywords: sea earthquake, precise location, aftershock detection, seismicity

1. Introduction

About 15km away from the southwest Jeju island, ML4.9 moderate size Seogwipo earthquake has occurred with several aftershocks on 12th Dec 2021 (Fig. 1). It produced a maximum intensity of V near Jeju island and III inland the Republic of Korea. And this area has relatively high seismicity than its surroundings.

To know how many earthquakes have been occurred in the study area, we searched for more aftershocks that did not detect at KMA (Korea Meteorological Administration) using the Matched-Filter (M.F.) small earthquake detection method.

The sea of Jeju island does not have a defined 1-D velocity model. So, we used two kinds of location methods, VELELLIPSE (Kim et al., 2014) and HYPOELLIPSE (Lahr, 1999), to figure out the rough velocity structure of the study area and compare each analyzed location result. VELELLIPSE is a combined method by HYPOELLIPSE, one of the hypocentral inversion methods, and the velocity updating algorithm. Because this method is effective for location analysis by applying to an area where a 1-D velocity structure model has not been developed, we adopted this for this area.

Using the VELELLIPSE and HYPOELLIPSE location methods addressed above, we relocated 21 KMA catalog events (Table. 1) over the ten days following the ML4.9 mainshock and located some of the 49 events detected in M.F during the same day. Then we calculated the focal mechanism solutions using FOCMEC (Snoke et al., 2003) of the mainshock and large enough aftershocks and compared them with the location trend of the aftershocks.

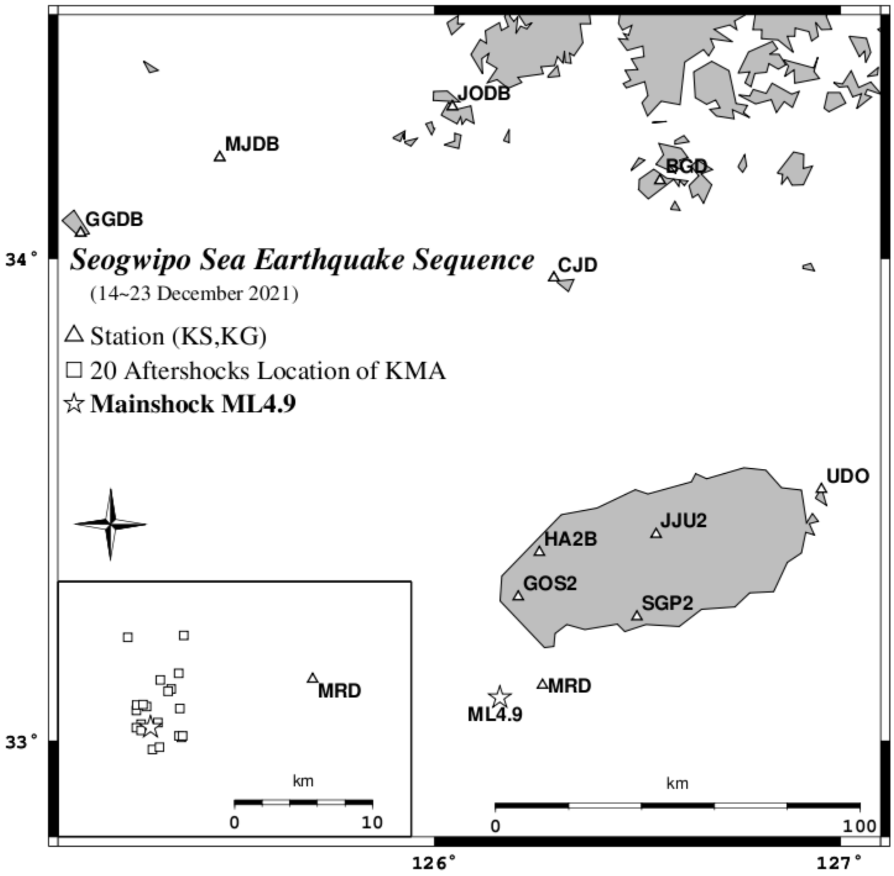

Fig. 1 – The map of Seogwipo sea earthquake sequence. Triangles are used stations for earthquake location. Squares show the location of 20 aftershocks from KMA catalog. A star is the location of mainshock from KMA catalog.

*Table 1. KMA catalog including 2021 Seogwipo earthquake sequence and past **M3** events*

NO	Origin Time	ML	Depth (km)	Max, Intensity	Lat.	Lon.	aftershock	Earthquake name
1	2005-06-15 07:07:02	3.9			33.06	126.17		
2	2005-06-15 07:37:47	3.0			33.00	126.15		
3	2014-05-15 08:46:51	3.4	18		33.00	126.21		
4	2021-12-14 17:19:14	4.9	17	V	33.09	126.16		2021 Seogwipo
5	2021-12-14 17:29:05	1.3	15	I	33.08	126.16	O	2021 Seogwipo
6	2021-12-14 17:29:34	1.5	8	I	33.12	126.17	O	2021 Seogwipo
7	2021-12-14 17:36:54	1.7	18	I	33.10	126.16	O	2021 Seogwipo
8	2021-12-14 18:02:27	1.6	18	I	33.10	126.16	O	2021 Seogwipo
9	2021-12-14 18:23:10	1.7	17	I	33.09	126.15	O	2021 Seogwipo
10	2021-12-14	1.6	12	I	33.09	126.18	O	2021 Seogwipo

	18:24:58							
11	2021-12-14 19:02:40	1.5	10	I	33.10	126.15	O	2021 Seogwipo
12	2021-12-14 19:08:51	1.6	16	I	33.09	126.18	O	2021 Seogwipo
13	2021-12-14 19:14:46	1.6	17	I	33.10	126.15	O	2021 Seogwipo
14	2021-12-14 20:45:32	1.3	16	I	33.08	126.18	O	2021 Seogwipo
15	2021-12-14 22:02:01	1.5	17	I	33.09	126.15	O	2021 Seogwipo
16	2021-12-14 22:03:49	1.5	15	I	33.08	126.17	O	2021 Seogwipo
17	2021-12-14 22:36:33	1.3	14	I	33.08	126.16	O	2021 Seogwipo
18	2021-12-15 09:32:33	1.7	17	I	33.09	126.15	O	2021 Seogwipo
19	2021-12-15 15:06:47	2.8	14	II	33.14	126.15	O	2021 Seogwipo
20	2021-12-16 00:16:53	1.7	17	I	33.11	126.17	O	2021 Seogwipo
21	2021-12-16 21:03:03	1.4	13	I	33.11	126.17	O	2021 Seogwipo
22	2021-12-17 06:22:10	3.2	18	III	33.12	126.18	O	2021 Seogwipo
23	2021-12-18 23:50:49	1.9	16	I	33.09	126.16	O	2021 Seogwipo
24	2021-12-22 21:14:27	1.7	19	I	33.14	126.18	O	2021 Seogwipo

2. Matched-Filter

A total of 21 earthquakes were recorded in the catalog of the KMA in 10 days after the ML4.9 Seogwipo earthquake. The study area has relatively high seismicity than its surroundings. There had been three M3 events (Table. 1), two in 2005 and one in 2014, before the Seogwipo earthquake. To better understand the properties of this region, we used the Matched-Filter method to detect small events not recorded in the KMA catalog.

We used the 20 aftershocks of the Seogwipo earthquake sequence as template events and continuous waveforms in 10 consecutive days (from 14 to 23 December 2021) as traces. Those template events and traces are band-pass filtered 3 to 6. We cut the template event by 2 secs (0.5 sec before and 1.5 secs after the picked S-wave arrival time by TauP; Crotwell et al., 1999) for matching with traces. And Cross-Correlation Coefficient(C.C.) detection threshold set the 0.5 with conservative 10 times MAD. After the Matched-Filter process, we found 49 new small earthquakes (Fig. 2) that do not record in the KMA catalog.

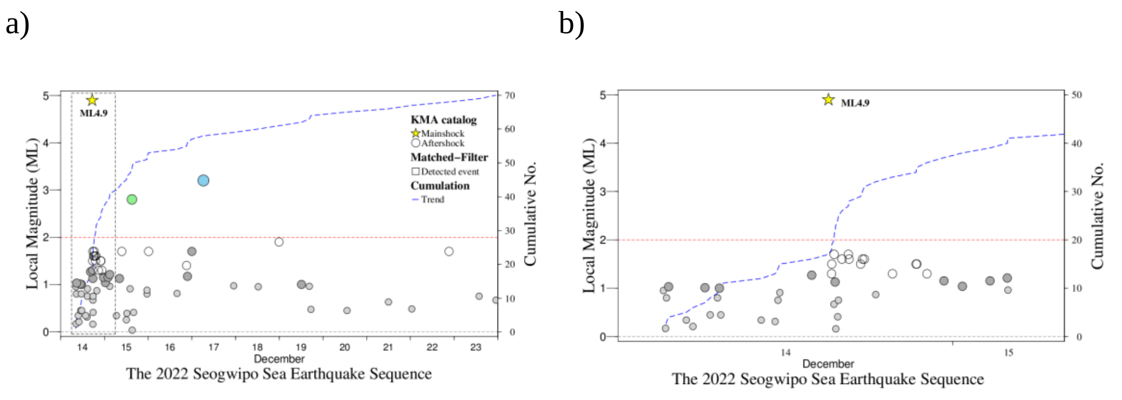

Fig. 2 – a) Time-ML graph with KMA catalog (colored and open circles; Table 1. No.5 to 24) and Matched-Filter catalog (shaded circles; Table 2.) with cumulative number of the Seogwipo earthquake sequence. A star is the mainshock, blue and green circles are large aftershocks (Table 1. No.22 and No.19) from KMA catalog. b) Inner square of a.

Table 2. Matched-Filter catalog, the shaded event numbers are located with VELELLIPSE and HYPOELLIPSE (35 of 49).

No.	Date	Time (UTC)	Relative M	C.C.	MAD
1	2021-12-14	08:26:31.367	0.95	0.6924	12.0202
2	2021-12-14	08:33:26.567	0.17	0.6342	10.9153
3	2021-12-14	08:36:35.387	0.80	0.6268	10.8823
4	2021-12-14	08:42:48.347	1.03	0.5847	10.4601
5	2021-12-14	09:39:52.447	0.34	0.6311	10.8495
6	2021-12-14	10:01:32.507	0.21	0.6659	11.6499
7	2021-12-14	10:40:26.127	1.01	0.7237	12.9422
8	2021-12-14	10:57:14.087	0.45	0.5771	10.0965
9	2021-12-14	11:21:07.467	0.80	0.6557	11.5807
10	2021-12-14	11:26:54.007	1.00	0.6220	10.6190
11	2021-12-14	11:31:19.687	0.45	0.5976	10.2739
12	2021-12-14	13:42:04.247	0.34	0.5794	10.3608
13	2021-12-14	14:26:45.407	0.31	0.5550	10.2595
14	2021-12-14	14:35:55.707	0.75	0.5487	10.4769
15	2021-12-14	14:42:12.327	0.91	0.7647	13.2770
16	2021-12-14	16:24:32.947	1.27	0.5657	10.1207
17	2021-12-14	17:36:10.947	0.67	0.6945	12.0568
18	2021-12-14	17:40:16.727	1.13	0.6962	12.0877
19	2021-12-14	17:42:53.827	0.16	0.7124	12.4632
20	2021-12-14	17:48:35.167	0.41	0.5781	10.0364
21	2021-12-14	17:50:36.107	0.75	0.6641	11.8765
22	2021-12-14	19:51:39.166	0.87	0.6783	12.1292
23	2021-12-14	23:31:47.486	1.15	0.5813	10.1738
24	2021-12-15	00:31:18.248	1.04	0.8406	14.9658

25	2021-12-15	02:00:04.068	1.15	0.5860	10.2171
26	2021-12-15	02:55:28.688	1.21	0.8051	15.0013
27	2021-12-15	02:58:08.868	0.96	0.7733	13.7673
28	2021-12-15	06:36:57.447	0.34	0.5838	10.8786
29	2021-12-15	08:18:45.947	1.13	0.8163	15.2110
30	2021-12-15	12:03:44.007	0.25	0.6593	11.6148
31	2021-12-15	12:17:11.667	0.39	0.5762	10.0473
32	2021-12-15	14:06:40.687	0.91	0.6595	11.4629
33	2021-12-15	15:16:12.887	0.03	0.6116	11.3959
34	2021-12-15	16:00:46.767	0.41	0.6924	13.0165
35	2021-12-15	23:22:01.506	0.88	0.6303	11.7665
36	2021-12-15	23:22:29.946	0.80	0.5490	10.6334
37	2021-12-16	15:54:38.267	0.81	0.5935	10.5697
38	2021-12-16	21:38:43.666	1.17	0.5405	10.0416
39	2021-12-17	00:02:15.088	1.70	0.8582	15.8934
40	2021-12-17	23:02:24.026	0.97	0.5537	10.2540
41	2021-12-18	12:24:06.527	0.95	0.7308	13.7975
42	2021-12-19	12:15:20.247	1.00	0.6502	11.5900
43	2021-12-19	16:27:47.427	0.96	0.5326	10.4367
44	2021-12-19	17:22:12.067	0.47	0.5856	10.4394
45	2021-12-20	13:16:45.987	0.45	0.5993	11.0315
46	2021-12-21	11:58:57.927	0.63	0.7498	13.9675
47	2021-12-22	00:45:48.788	0.48	0.5393	10.2573
48	2021-12-23	13:42:23.387	0.75	0.5932	11.3861
49	2021-12-23	22:58:29.526	0.67	0.5755	10.7754

3. VELELLIPSE (Kim et al., 2014)

VELELLIPSE location method is a combination method by HYPOELLIPSE, one of the hypocentral inversion methods, and the velocity updating algorithm. This method yields an optimum 1-D velocity model by minimizing travel time residuals at each layer of the initial model. Then calculate the earthquake location with the revised 1-D velocity model. So, that is the better location analysis at the region for no defined velocity model.

Using VELELLIPSE and HYPOELLIPSE, we relocated the KMA catalog (Fig. 3) and successfully located 35 small earthquakes (Fig. 4) of 49 detections by Matched-Filter method.

a) b)

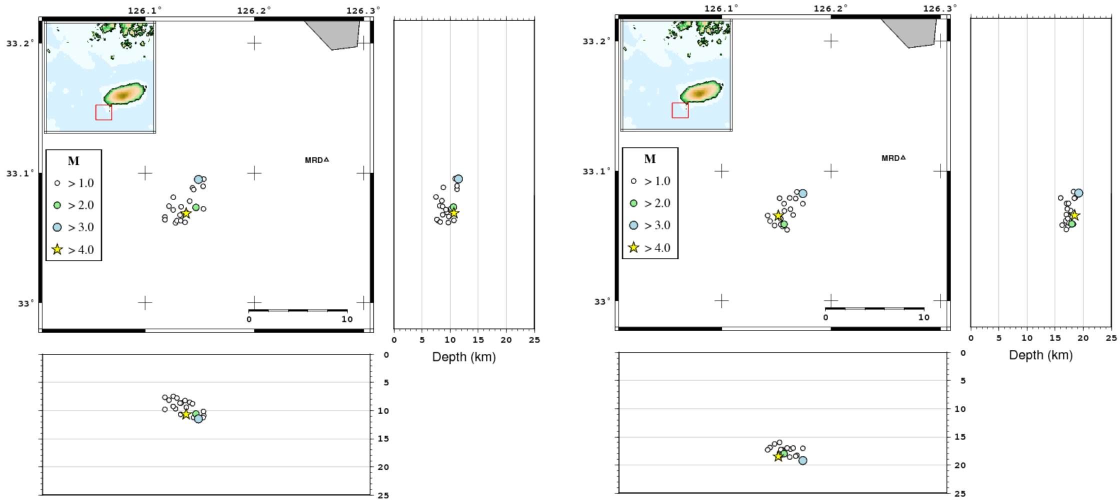

Fig. 3 – Relocation of KMA (Korea Meteorological Administration) catalog (Table. 1; No.4 to 24) with IASP91 1-D velocity model. a) VELELLIPSE b) HYPOELLIPSE

a) b)

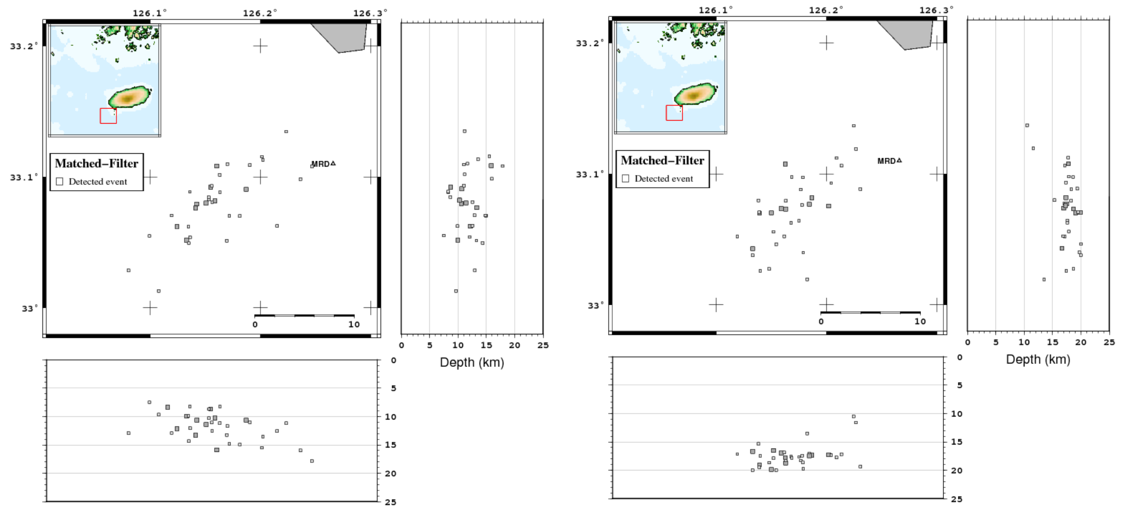

Fig. 3 – Location of Matched-Filter detection catalog (Table. 2; shaded) with IASP91 1-D velocity model. a) VELELLIPSE b) HYPOELLIPSE

Table 3. Focal mechanism solutions of the Seogwipo mainshock estimated by using FOCMEC program. (No. from Table. 1)

No.	S1	D1	R1	S2	D2	R2	P_tr	P_pl	T_tr	T_pl	B_tr	B_pl
4	97.48	47.18	-30.91	209.63	67.87	-132.8	73.35	48.33	329.09	12.37	228.86	39

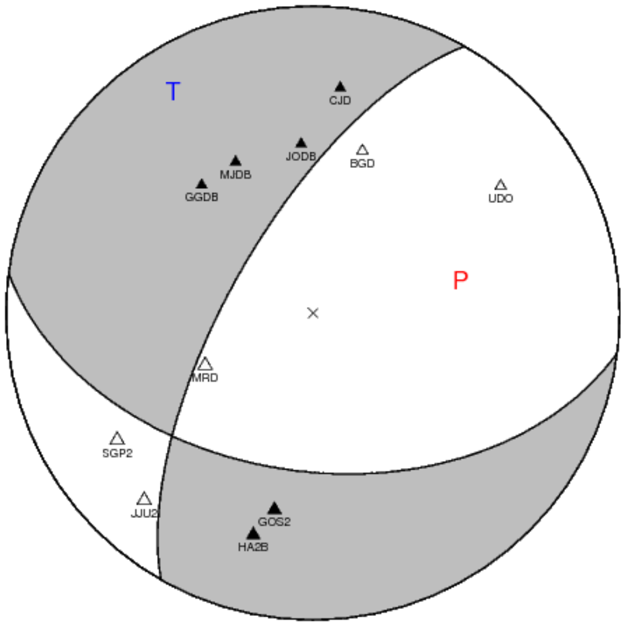

Fig. 4 – Focal mechanism solution of the ML4.9 Seogwipo earthquake (Table. 1 – No. 4)

4. Conclusions

The study area about 15km far from Jeju island to the southwest have relatively high seismicity. There have been a few M3 events before, and recently over M4 Seogwipo earthquake occurred with several aftershocks. This earthquake sequence produced a maximum intensity of V near Jeju island. For more detailed seismicity here, by using Matched-Filter, we detected 49 aftershocks does not record in KMA catalog in 10 days after the Seogwipo earthquake and located 35 events of detections to distinguish the rupture process. Then we found the NE trend of aftershocks movement and this result show naturally similar to the focal mechanism solution of the ML4.9 mainshock and we can guess the fault line should align with this. In future work, we will estimate source parameters as corner frequency, stress drop, and character of this area.

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