Chapter 2

Repeating earthquake identification

2.1 Data limitation in eastern Taiwan

2.1.1 Original catalog

3387 earthquakes in the Chihshang area from the CWBSN catalog were first examined in the RESs identification. These events occurred in the Chihshang fault region (box, Fig. 2-1) during January 1, 1991 through the day before the December 10, 2003 $M_L$ 6.4 earthquake. The reason we exclude the 2003 $M_L$ 6.4 aftershocks and subsequent data from this study is that the temporal variation in properties of the medium related to large earthquakes may have impact on the repeating earthquake identification scheme used in this study (time-invariant velocity model). Magnitudes of these events range from $M_L$ 1.9 to 5.4. Magnitude statistics indicate that the CWBSN catalog is complete down to $M_L$ 1.9. Seismograms for these events were recorded by the short-period stations of the CWBSN at sampling rates of 50, 100, and 200 Hz, with rate dependent on the time period of data acquisition. For this study, we used vertical component seismograms from 7 CWBSN stations having relatively low noise level (solid triangles in Fig. 2-1). Among these stations, only TWF1 and CHK are local to the Chihshang fault, with CHK being closest. A significant fraction of the seismicity occurs offshore. Consequently the station coverage is relatively one-sided.
Fig. 2-1: Mapview of seismicity and RESs in the Chihshang area. (a) Geodynamic framework of Taiwan. Open arrow indicates relative motion between Philippine Sea plate and Eurasian plate in Taiwan Region [Yu et al., 1997]. (b) The Chihshang fault segment and the Chihshang study area (box). HypoDD relocation of M ≥ 3 seismicity during the study period are shown as gray dots. The 7 seismic stations used in this study are shown as black triangles, others with relatively lower SNR are shown as open triangles. Locations of the 30 repeating sequences that we found are shown as black solid circles. Inset shows the plate-tectonic of Taiwan and the location of the LVF. Stars are the M ≥ 6 historical earthquakes that occurred on the Chihshang fault.

2.1.2 Similar event search

Our first step in searching for repeating events in the Chihshang area involved a comprehensive characterization of event similarity using waveform cross-correlation [Aster and Scott, 1993] and CHK seismograms for all event pairs in the study zone (box, Fig. 2-1). To reduce the computation effort, only seismograms recorded at CHK station (i.e., the station with the best signal-to-noise ratio for Chihshang fault events) were used. In general, the standard error of the CWBSN epicenters is ~1 km in both horizontal and vertical directions.

For most of the study period, CHK seismograms were recorded at 100 samples per second (sps). For the similar events search, those recorded at 50 or 200 sps were re-sampled at 100 sps, and these seismograms were bandpass filtered from 1 to 10 Hz. Maximum cross-correlation coefficient (ccc) between all seismogram pairs were then
determined using a 10.5 second window beginning 0.5 second before the P-arrival. Those events having seismogram pairs with ccc’s greater than 0.80 were selected as similar event pairs. Similar event pairs were then grouped into similar event clusters whenever pairs shared common events. The resulting event clusters represent an intermediate stage data set from which repeating event sequences were derived.

2.1.3 Repeating earthquake sequence identification

A basic assumption in deriving deep slip rates from RESs [Nadeau and McEvilly, 1999] is that events in a given sequence re-rupture the same fault patch and produce earthquakes having similar magnitude, waveforms, and locations. The deep slip method is also most accurate when all repeated ruptures that occurred during the study period have been identified (i.e., the sequences are complete). For deep slip rate estimation in the Chihshang area therefore, it is important to define RESs that have these properties.

While the similar event clusters derived in the previous section provide a reduced catalog from which RESs can be derived, any given cluster may be comprised of multiple RESs and may also contain additional similar events that do not occur as repeated earthquakes. Consequently, further discrimination and decomposition of the similar event clusters into RESs is necessary.

Previous approaches to doing this have used criteria based on similarity in location [e.g., Vidale et al., 1994; Ellsworth, 1995; Rubin et al., 1999; Schaff and Beroza, 2004] or in waveform [Nadeau et al., 1995; Matsuzawa et al., 2002; Igarashi et al., 2003; Uchida et al., 2003; Nadeau and McEvilly, 2004; Matsubara et al., 2005]. Methods based on the similarity of locations typically rely on relative event delay time measurements at sub-sample precision to reduce relative location uncertainties to be less than the expected rupture dimension of the events (generally a few 10’s of meters for typically small magnitude repeaters based on assumed circular rupture and 3 MPa stress drop), and application of these methods have proven to be generally successful in regions with well distributed station coverage, and accurately timed data.

However, in regions (e.g., offshore) where spatial coverage is sparse or one sided, where significant changes in station distribution occur over time, or where starting catalog origin times are inaccurate; establishing effective co-location of repeated events using relative event relocation methods can become problematic [Ross et al., 2001]. Furthermore, inaccurate or inconsistent timing of recorded data also contribute significantly to inaccurate relative relocations [Rubin, 2002] and can cause repeating events to be either missed or erroneously included in repeating
sequences. Similarly, missed repeats and/or the inclusion of non-repeating events into sequences can also occur using waveform similarity as a criterion, particularly when SNR is low, short data windows are used, and/or when excessive filtering of the waveforms is used [Uchida et al., 2004].

2.1.4 Data limitations in the Chihshang area

The relatively sparse and one-sided coverage of the CWBSN stations in the Chihshang area (Fig. 2-1) coupled with relatively low SNR and unstable noise characteristics (Fig. 2-2) complicate the task of defining complete and accurate RESs in this area. During our analysis we have also found that significant origin time errors and/or timing inconsistencies exist in the CWBSN data set, further complicating the task of sequence definition.

The effect that timing errors and inconsistencies on earthquake relocation and sequence definition in the Chihshang area can be illustrated by comparing double-difference relocations based on standard travel time estimates and relocations derived from travel time estimate using only S-P times and an assumed Vp/Vs velocity model. The later approach, which we refer to as the Vp/Vs method, requires both P- and S- phase alignments, and the assumption of a reasonable Vp/Vs model. Hence it is not always a viable approach for determining relative location of repeating events (especially where coverage is sparse and the SNR is marginal), and absolute location accuracy is limited due to the Vp/Vs model assumption. However the method has the distinct advantage of removing the dependency of relocations on catalog origin times and absolute timing inconsistencies among stations in a network. When used in conjunction with similar event data, therefore, it can be a useful tool for identifying data plagued with large origin time errors and/or inconsistency in timing among stations.
Fig. 2-2: Typical signal to noise characteristics of the CWBSN stations in eastern Taiwan. Unfiltered vertical velocity seismograms are shown from 3 events of the RES CH16 (Table 2-1) recorded at 3 of the 7 stations used in the study. Dates and maximum cross-correlation coefficients (ccc) for 10.5 sec data windows starting 0.5 sec before P and relative to the reference event (ccc = 1.0) are shown on the right. Signal to noise is good and background noise relatively stable at station CHK (closest to the Chihshang fault). At other stations, however, signal to noise is significantly lower and temporally variable for the events we examined.

2.2 Vp/Vs relocation method

2.2.1 Travel times using S minus P and assumed Vp/Vs

Consider single earthquake source whose P-phase travel time, \( t_p \), and S-phase travel time, \( t_s \), along the receiver to station distance \( x \), has a relation to P wave velocity \( (V_p) \) and S wave velocity \( (V_s) \) as \( V_p = x / t_p \) and \( V_s = x / t_s \). The time difference between P- and S- phase arrival times (\( S_mP \), S minus P time) by formula \( S_mP = t_s - t_p \) can be related to the constant \( V_p/V_s \) ratio by:

\[
\frac{V_p}{V_s} \frac{t_p}{t_s} = \frac{S_mP + t_p}{t_t} = \frac{t_p + S_mP}{t_t} = 1 + \frac{S_mP}{t_t},
\]  

(2.1)

which leads to
\[ tt_p = S_m P /((V_p / V_s) - 1) \quad \text{and} \quad (2.2) \]
\[ tt_s = -S_m P /((1 - (V_s / V_p))) \quad , \quad (2.3) \]

where \( S_m P \) is the S minus P time for a given event at a given station and \( V_p/V_s \) and \( V_s/V_p \) are an assumed \( V_p/V_s \) ratio and its reciprocal, respectively. For standard double-difference relocations [Waldhauser and Ellsworth, 2000], \( tt_p \) and \( tt_s \) are determined by subtracting the origin times of the events from the arrival times. In contrast, the \( V_p/V_s \) method determines \( tt_p, tt_s \) using the relationships in eqs. (2.2) and (2.3). No origin time information is used in determining \( tt_p \) and \( tt_s \) in these equations, and the dependence on absolute timing accuracy is also reduced to how accurately the rate of sampling between the P and S phase arrivals is maintained. Therefore, assuming accurate sampling over the relatively short interval between S- and P-, eqs. (2.2) and (2.3) can provide travel-time estimates that are largely free of origin time errors and timing inconsistencies among station clocks, both of which can contribute significantly to inaccuracies in relative relocations of earthquakes [Ross et al., 2001; Rubin, 2002].

Consider two similar events whose relative P- and S- phase arrival times have been determined using cross-correlation. Consider two earthquake sources that have S-P time of \( S_m P_1 \) and \( S_m P_2 \), the differential P travel time \( (dPtt_p) \) and the differential S travel time \( (dPtt_s) \) between the two events can be determined from \( S_m P_1 \) and \( S_m P_2 \):

\[ dPtt_p = \frac{S_m P_2}{V_p V_s - 1} - \frac{S_m P_1}{V_p V_s - 1} = \frac{S_m P_2 - S_m P_1}{V_p V_s - 1} \quad \text{and} \quad (2.4) \]
\[ dPtt_s = \frac{-S_m P_2}{1 - V_p / V_s} + \frac{S_m P_1}{1 - V_p / V_s} = \frac{S_m P_1 - S_m P_2}{1 - V_p / V_s} \quad . \quad (2.5) \]

Using the above algorithms, one can obtain the double-difference relocation result by minimizing uncertainty from picking error. Based on the ccc estimate at individual P-window and S-window, the calculated \( dPtt_p \) and \( dPtt_s \) are weighted by the square ccc during the relocation process.

It should be pointed out, however, that because an assumed \( V_p/V_s \) ratio is used in eqs. (2.2) and (2.3), the absolute locations of relocated events using these equations may not be particularly accurate. However, because we are primarily concerned here with the ‘relative’ rather than ‘absolute’ locations of similar events, a \( V_p/V_s \) ratio that
is approximately correct using eqs. (2.4) and (2.5) and is generally sufficient for assessing the degree of location scatter introduced by large origin and inter-station timing errors.

2.2.2 Effect of timing errors on relocations

The effect that origin and inter-station timing errors can have on relative locations in the Chihshang area can be illustrated by comparing double-difference relocations (hypoDD [Waldhauser, 2001]) based on standard travel time estimates with those based on travel time estimates from eqs. (2.4) and (2.5) (Fig. 2-3).

In Fig. 2-3, the same cross-correlation aligned phase data (both P and S, to sub-sample precision) and weighting are used for the hypoDD inversions of a similar event cluster of 7 earthquakes using the two types of travel time estimates. A Singular Value Decomposition (SVD) inversion was also used in both cases, and all other inversion parameters are identical. Panels a and b show relocations using travel times calculated by subtracting catalog origin times from cross-correlation aligned phase arrival times (i.e. standard relocations). Panels c through f, show relocations using travel times determined using eqs. (2.4) and (2.5) with an assumed Vp/Vs ratio of 1.78 (i.e., Vp/Vs relocations).

Average horizontal and vertical uncertainties reported by hypoDD for the standard relocations are 290 and 340 m, respectively (Figs. 2-3a and 2-3b). HypoDD uncertainties for the Vp/Vs relocations are generally less than 20 m (Figs. 2-3c through 2-3f). Because all parameters other than the estimated travel-times are identical, the large reduction in location scatter for the Vp/Vs relocations can be attributed primarily to the reduced dependence on origin and/or inter-station timing errors afforded by eqs. (2.4) and (2.5).

The Vp/Vs relocations also show that what had originally appeared to be 7 earthquakes with distinctly different locations in the standard relocation results actually resolve themselves into 2 sites with 3 events each that are primarily overlapping. The remaining event was excluded by hypoDD as an airquake. We eventually identified the overlapping events at the 2 sites as members of two different RESs (CH14 and CH15 in Table 2-1), and that the airquake did not belong to an identifiable repeating sequence. Examples of the improvement of earthquake relocation are shown in Fig. 2-4, where the events rupture approximately the same fault patch in each case.
Fig. 2-3: RESs relocation using hypoDD and Vp/Vs method. Double-difference relocations of a similar event cluster (M2.5-2.8) using waveform cross-correlation data (panels a and b), and Vp/Vs method (panels c and d). Panels e and f zoom into locations of interest in panels c and d. Earthquakes are plotted as circles of dimensions corresponding to their magnitude assuming a 3 MPa constant stress drop source. Crosses indicate uncertainties from hypoDD inversion. Note, event 7 was excluded as an airquake by the hypoDD inversion (panels c and d). Among the 7 stations used in the study, only 3 stations had high enough waveform similarity to be obtained for event 7. Airquake exclusions are not uncommon when stations coverage is sparse, as in this case.

Additional tests using other similar event clusters indicate that the exclusion of events by hypoDD and the timing and associated relative location errors illustrated by the example in Fig. 2-3 are fairly common for the Chihshang area. These errors in conjunction with the sparse and one-sided coverage of the CWBSN stations, intermittent station outages for the sparse network, and the temporally unstable noise characteristics of the CWBSN records (Fig. 2-2) make comprehensive and systematic identification of Chihshang repeating events using a location based approach impractical.

The accuracy of repeating event identification based solely on a waveform similarity criteria is also somewhat limited for small magnitude repeaters in the Chihshang area due to the small number of stations, the large variation in event-to-station travel paths, and the generally low and temporally variable SNR.
Fig. 2-4: RESs relocation using hypoDD and Vp/Vs method for CH2 and CH6 (Table 2-1). Double-difference relocations of RESs CH2 and CH6 using waveform cross-correlation data (panels a and b), and Vp/Vs method (panels c and d). Panels e and f zoom into locations of interest in panels c and d. Earthquakes are plotted as circles of dimensions corresponding to their magnitude assuming a 3 MPa constant stress drop source. Crosses indicate uncertainties from hypoDD inversion.
2.3 Composite selection criteria

Given the limited quantity and quality of seismic data in the Chihshang area and the need to identify RESs as accurately and completely as possible for inferring deep fault slip rates, we have chosen a more robust approach for identifying RES in the Chihshang area (i.e., a composite selection approach). The approach incorporates both waveform similarity (wfs) and differential S-P ($dS_{mP}$) time information (at sub-sample precision) and allows exclusion of outliers in the wfs and $dS_{mP}$ data. By relying only on wfs and $dS_{mP}$ time statistics on a station by station basis, the method also effectively eliminates errors introduced by inaccurate origin times and inter-station timing.

Two key observables of earthquakes re-rupturing the same fault patch are their effective co-location and the similarity of their seismograms throughout the P-, S- and coda phases. The composite selection approach constrains repeated event locations by requiring the $dS_{mP}$ times between repeating event pairs to be small, and constrains seismogram similarity by requiring the wfs (as measured using maximum waveform cross-correlation coefficient (ccc) between repeating events) to be high for a long data window and over a broad frequency band.

In an idealized situation, where ruptures of the repeated events are identical, noise contributions are non-existent, and propagation and recording characteristics are time invariant, $dS_{mP}$ times between repeated events should be zero and their seismograms should be identical (e.g., $ccc \approx 1$) at all stations. In nature, however, subtle yet significant temporal variations in propagation velocities are known to occur [Rubin, 2002] as are small variations between the ruptures of repeating events (e.g., seismic moments [Vidale et al., 1994; Nadeau and Johnson, 1998; Nadeau and McEvilly, 1999]). Such variations translate into deviations from idealized expectation in the $dS_{mP}$ time and ccc measurements for repeated events. However, when data quality is good, these deviations are generally relatively minor, and there is usually a clear distinction of the $dS_{mP}$ time and ccc statistics among repeated event pairs versus the same statistics obtained for event pairs that are not repeats, and this distinction can be used as a basis for repeating event identification.

When the data quality is lower (e.g., in the Chihshang area), the distinction between repeated and non-repeated event statistics is less clear and unless compensated for can confound efforts to accurately define repeating event sequences. To compensate for the lower data quality in the Chihshang area, therefore, we take the tact of reducing the sensitivity of our identification scheme by excluding statistical outliers.

This is done by the following manner. First, we define an event similarity space...
[dS_mP, ccc] (Fig. 2-5). We then populate this space with similarity point measurements (dS_mP, ccc) where each point represents the dS_mP and ccc measurements between two events for a given station. All event pair combinations for a similar event group are considered. Ccc statistics are determined using a 10.5 second window beginning 0.5 second before the P-arrival with bandpass filter of 2-18 Hz. DSmP statistics were determined using two 2.5 second windows beginning 0.5 second before the P-arrival and S-arrival.

In an idealized case, similarity points for all stations should plot at (dS_mP=0.0, ccc=1.0) for two identical (repeated) earthquakes. However, deviations of the similarity points from idealized expectations generally occur, due both to true differences between event sources and to noise inherent in the data. Therefore, we break the similarity space into three regions (Fig. 2-5a). Region A includes both region B and C. Region B includes region C. In region A excluding B and C, the similarity points are indicative of either event pairs that are highly dissimilar or of similarity data for specific stations that are unreliable due to the various noise sources discussed previously. In region B and including C, similarity points are considered to be relatively reliable, and points plotting in region C represent (dS_mP, ccc) data with the highest degree of similarity.

Empirical tests using a subset of the event pairs where sufficient data quantity and quality exists for confirmation of patch re-rupture through relocation using the Vp/Vs method show that the similarity points for repeated event pairs generally plot in region C, though a small fraction of points for repeated events may also plot in the larger region B, and in some situations (i.e., when station data is of poor quality) in region A (Fig. 2-5b and 2-5c). To help compensate for the ambiguity this poses when identifying repeated events, we use the following composite criteria (again based on empirical testing) for defining repeated event pairs within a similar event group. For two events to be considered a repeating pair at least 75% of their similarity points must lie within region B, and of those points at least 50% must also lie within region C. Once repeating pairs have been selected, they are organized into repeating event sequences. Each sequence is a collection of events that are linked by the composite criteria to at least one other member of the sequence.
Fig. 2-5: (a) Schematic illustration of the criteria used for repeating earthquake identification in the study area. $D_{SP}$ is the difference in S-P time between two events. $C_{cc}$ is the maximum cross-correlation coefficient between two events. Region A is the area for overall measurements, region B is the area of $C_{cc} \geq 0.70$ and $D_{SP} \leq 0.02$, and region C is the area of $C_{cc} \geq 0.85$ and $D_{SP} \leq 0.012$. (b) $C_{cc}$, $d_{SP}$ statistics for a group of similar events compared to event 3. Each point maps the $D_{SP}$ and $C_{cc}$ for an event pair at a single station. Points with identified symbols are for the same event paired with event 3. (c) Zoom in of region B. Event 2 and 6 pass the selected criteria discussed in the text, and therefore are grouped into a repeating sequence with event 3. Those three repeating events belong to sequence CH14 in Table 2-1.
2.4 Summary

2.4.1 Similar event catalog preparation

1) Prepare seismograms of local earthquakes from the closest station (CHK station in this study) using a 10.5 second window beginning 0.5 second before the P-arrival, re-sample at 100 sps, and bandpass filtered from 1 to 10 Hz.
2) Maximum ccc between all seismogram pairs should be greater than 0.80. These events are selected as similar event pairs.
3) Similar event pairs are then grouped into similar event clusters whenever pairs shared common events.

2.4.2 Master-pair selection

1) Collect data from different stations (at least 5 stations) for each similar event.
2) Determine the ccc and $d_{mP}$ information (at sub-sample precision) for each similar event pair. Ccc statistics are determined using a 10.5 second window beginning 0.5 second before the P-arrival with bandpass filter of 2-18 Hz. $d_{mP}$ statistics were determined using two 2.5 second windows beginning 0.5 second before the P-arrival and S-arrival. Note that the time window depends on the termination of S-wave coda.
3) Define an event similarity space [$d_{mP}$, ccc]. We then populate this space with similarity point measurements ($d_{mP}$, ccc) where each point represents the $d_{mP}$ and ccc measurements between two events for a given station. All event pair combinations for a similar event group are considered.
4) Break the similarity space into three regions.
   - Region A: overall ccc and $d_{mP}$ estimates
   - Region B: ccc $\geq$0.70 and $d_{mP} \leq$ 0.02 sec
   - Region C: ccc $\geq$ 0.85 and $d_{mP} \leq$ 0.012 sec

In region A excluding B and C, the similarity points are indicative of either event pairs that are highly dissimilar or of similarity data for specific stations that are unreliable due to the various noise sources discussed previously. In region B and including C, similarity points are considered to be relatively reliable, and points plotting in region C represent ($d_{mP}$, ccc) data with the highest degree of similarity.
5) Determine the master pair showing the best condition in earthquake colocation and waveforms similarity for each similar event cluster. The criteria for master event-pair selection we adopt are described below.
Time separation is longer than 0.5 yr.
Number of data (measurements from different stations) is larger than 4, which is more than 50% of total stations used in this study.
The data number in region B (N_B) should be larger than 50% of the number in region A (N_A), and the data number in region C (N_C) should be greater than 50% of number in region B.
Size difference should be less than 0.3 in local magnitude unit.

6) When the pairs pass the above criteria, they are selected as the potential master-pairs. If all pairs in a given cluster fail to pass the criteria, we regard this cluster less confident to be a potential repeating sequence and stop the following identification procedures. Care must be taken when the potential master-pairs have one event in common. Under this situation, we select the pair showing the larger N_C as the optimal one.

2.4.3 Defining repeating event-pairs

The events in the previously prepared similar event catalog are paired to the selected master-pair. For two events to be considered a repeating event-pair at least 75% of their similarity points must lie within region B, and of those points at least 50% must also lie within region C. Once repeating pairs have been selected, they are organized into repeating event sequences. Each sequence is a collection of events that are linked by the composite criteria to at least one other member of the sequence.

Based on the composite selection criteria, we identified 58 RESs in eastern Taiwan, their locations, magnitudes, and source parameters are shown in Table 2-1.
### Table 2-1 Repeating earthquake sequences in eastern Taiwan

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<th>ID</th>
<th>N</th>
<th>Lon</th>
<th>Lat</th>
<th>Depth</th>
<th>Ml</th>
<th>Tr</th>
<th>slip rate</th>
<th>duration</th>
<th>COV in Mo</th>
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<td>(yr)</td>
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<td>23.897</td>
<td>18.86</td>
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<td>0.59 - 0.86</td>
<td>13.43</td>
<td>2.32</td>
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<td>0.01</td>
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The Hualien, Chishang, and Taitung RESs clusters are denoted by H, CH, and TT in the first column, respectively. N represents the event number in each RESs. Tr represents the recurrence interval. Slip rate estimate is long-term slip rate from eq. (3.1). Duration is the lifetime of a sequence. The sequences with repeating events that only occurred in a very short time period (i.e., 6 yr in this study) is classified into burst type repeating sequences (B-type), whereas the sequence with longer than 6-yr duration is defined as non-B type. Non-B type sequences are further separated into quasi-periodic and aperiodic sequences based on the variation of recurrence time between events in a sequence, coefficient of variation (COV, standard deviation divided by the mean) in recurrence interval. Parameters highlighted in grey are the reliable slip rate estimates used in Chapter 3.3.