

Low frequency earthquakes (LFEs) in Guerrero seismic gap and systematic LFEs deep learning model

(ゲレロ地震空白域内の低周波地震と系統的 LFE 深層学習モデル)

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1. Introduction

Slow earthquakes, including slow slip events (SSEs), tectonic tremors, and low-frequency earthquakes (LFEs), play a crucial role in accumulating strain along subduction zone interfaces. Unlike fast ruptures that release stress abruptly, slow earthquakes evolve gradually and often localize near the transition between locked and creeping fault segments. In the Mexican subduction zone, the Guerrero seismic gap stands out as a region where frequent slow-slip events and tsunami earthquakes occur near the trench at the shallow portion of the subduction zone, despite the absence of recent large interplate earthquakes. The occurrence of shallow tectonic tremors suggests that aseismic slip may extend toward the trench; however, shallow LFEs have not yet been systematically characterized in comparison with shallow tectonic tremors.

Significant challenges arise from limited offshore observations and the inherent difficulty of detecting weak, transient signals embedded in noise. Short-duration tremors can be regarded as a part of the LFEs; therefore, this study first investigates shallow tectonic tremor activity using the envelope correlation method to detect both short-duration and long-duration tremors.

Subsequently, waveform stacking techniques with the traditional matched filter approach are applied to detect LFE signals in the Guerrero seismic gap. Recent advances in deep learning have opened new possibilities for high-resolution detection of such slow earthquakes. One objective of this thesis is thus to characterize shallow LFEs in the Guerrero seismic gap, to improve the objectivity and efficiency of tremor and LFE detection through machine-learning techniques, and to construct a systematic deep-learning model capable of identifying uncatalogued LFEs. These efforts aim to clarify the mechanical behavior of the shallow plate interface and its implications

for the earthquake cycle and tsunami generation in subduction zones. Overall, this thesis advances the understanding and detection of shallow LFEs and tremors in subduction zones, contributing to a better comprehension of slow-to-fast earthquake processes.

2. New Insight into shallow tectonic tremor and LFEs in the Guerrero seismic gap

Continuous seismic data recorded by ocean-bottom seismometers (OBS) from 2017 to 2019 were analyzed using a modified envelope cross-correlation method to detect tectonic tremors and a matched filter technique to identify LFEs. A total of 637 tremors and 205 LFEs were detected, representing the first identification of shallow LFEs in the offshore portion of the Guerrero seismic gap. These LFEs are mainly distributed near the trench and spatially coincide with negative gravity anomalies and subducting seamounts, suggesting that structural heterogeneities facilitate transient slip. Temporal variations reveal episodic bursts and migration of tremor activity, occasionally triggered by nearby large earthquakes, such as the 2018 Mw7.2 event. Some LFEs occur independently of tremor activity, likely associated with shallow slow ruptures in the tsunamigenic region. The spatial distribution of tremors and LFEs indicates a shallow transition from locking to stable sliding along the subduction interface. These results demonstrate that the Guerrero seismic gap hosts complex slip behavior governed by geological heterogeneity and variable coupling strength, providing new insight into the interaction between slow slip and potential tsunami-earthquake generation near the trench.

3. Machine learning clustering for tremor detection

The envelope cross-correlation method used for tremor detection has inherent limitations in clustering and event identification. To overcome these weaknesses, a machine-learning-based clustering approach was applied for reducing the subjectivity of traditional methods that depend on visual inspection. The technique extracts waveform features—such as amplitude ratios, frequency content, and temporal coherence—and groups similar signals into clusters representing tectonic tremors, local earthquakes, or noise. By classifying tremor-like signals according to statistical similarity rather than human judgment, this approach enhances both the accuracy and reproducibility of tremor identification. Applied to the Guerrero OBS dataset, the

clustering method efficiently distinguishes coherent tremor signals even under low signal-to-noise conditions, eliminating the need for manual screening. The resulting catalog of tremor candidates agrees well with detections from the envelope correlation method while detecting additional weak signals that were previously overlooked. This machine learning framework demonstrates strong adaptability to large, continuous datasets and provides an objective basis for precise tremor recognition. Overall, it bridges the gap between conventional seismic analysis and modern data-driven detection, paving the way for more reliable identification of tectonic tremor signals in offshore environments.

4. Training systematic deep learning model for detecting uncatalogued LFEs

The matched filter method is a powerful technique to detect LFEs, but it remains limited in identifying events that lack existing templates. To overcome this limitation, a convolutional neural network (CNN)-based deep learning model was developed to detect uncatalogued LFEs that cannot be recognized by conventional template-based approaches. The model incorporates multi-station waveform inputs and employs a Gaussian arrival-time labeling scheme to accommodate uncertainty in phase arrivals. A complete training pipeline was established, including waveform preprocessing, data labeling, model optimization, and performance evaluation using global LFE datasets from multiple subduction zones. Through data transformation and feature learning, the model captures the characteristic temporal patterns of LFEs, enabling the detection of subtle seismic signals without predefined templates. When applied to continuous OBS data from the Guerrero seismic gap, the model successfully identified a series of previously unrecognized LFEs, expanding the catalog of known LFE activity. These newly detected events reveal additional areas of slow slip and demonstrate the high sensitivity of the model to weak, low-frequency sources. The results confirm that deep learning provides a powerful and generalizable framework for LFE detection across diverse tectonic environments, representing a significant advance in the LFE study.

5. General discussion

The integrated analysis of multiple detection approaches provides a comprehensive view of slow earthquake processes in the Guerrero seismic gap. The combined results reveal that shallow LFEs and tremors are concentrated within a transition zone between locked and creeping regions, where variations in coupling and subducted topography govern slip behavior. Subducting seamounts and associated negative residual-gravity anomalies coincide with clusters of LFEs and tremors, suggesting that subsurface heterogeneities promote slow rupture or stable sliding. This heterogeneous structure likely acts as a barrier that prevents large interplate ruptures from propagating into the seismic gap, explaining its long-term quiescence. The coexistence of the tremors, the LFEs, and the small tsunami earthquake indicates a continuum of slow and fast slip behaviors along the shallow plate boundary in the Guerrero seismic gap. Among the detection techniques, the matched filter and deep learning approaches demonstrate complementary strengths in detecting the LFEs. The matched filter method, which relies on waveform cross-correlation with known templates, remains highly reliable for detecting events with similar source characteristics and low signal-to-noise ratios. It provides precise timing and amplitude information, allowing for robust catalog construction when suitable templates are available. However, its dependence on prior templates inherently limits its ability to capture previously unobserved or atypical LFEs. In contrast, the deep learning model developed in this study requires no predefined templates. By learning generalized waveform features from large and diverse datasets, it can recognize subtle, non-repetitive LFEs that would remain undetected by correlation-based methods. When applied to the same dataset, the model successfully identified additional LFEs that were not matched by existing templates, demonstrating its sensitivity to new or evolving source processes. Comparison with matched filter detections also provides an important validation framework, ensuring the physical reliability of machine-learning results. Together, these complementary approaches capture both stable, recurrent LFE families and more irregular, transient events, offering a more complete view of LFE activity. These findings highlight how hybrid detection strategies can significantly enhance the resolution and reliability of slow earthquake monitoring in subduction zones, offering new insights into the wide spectral range of slip behavior on the shallow subduction interface and their role in the generation of tsunami earthquakes.

6. Conclusion

Analysis of offshore seismic data, combined with the development of advanced detection algorithms, has yielded the first systematic catalog of shallow LFEs in the Guerrero seismic gap. The integration of machine learning and deep learning techniques enables efficient, objective detection of both tremors and LFEs, providing a more comprehensive view of slow earthquake activity near the trench. The spatial correlation of LFEs with geological anomalies and subducted seamounts underscores the critical role of structural heterogeneity in controlling slip behavior along the subduction interface. The discovery of previously uncatalogued LFEs demonstrates that a significant portion of seismic activity had remained undetected by conventional methods. These findings improve our understanding of the shallow slip behavior that bridges aseismic creep and tsunamigenic rupture, contributing valuable insights into the mechanics of subduction zones and the broader earthquake cycle.