

Seismic Waveform Modeling of the 2018 Flank Collapse of Anak Krakatau Volcano and Implications for Near-field Multi-source Tsunami Warning

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ABSTRACT

The 22 December 2018 flank collapse of Anak Krakatau volcano generated a destructive tsunami in the Sunda Strait without a preceding tectonic earthquake, highlighting the limitations of earthquake-based tsunami warning for non-seismic tsunami sources. Previous studies have established that collapse of the volcano's southwestern flank triggered the tsunami; however, the detailed force evolution and kinematic behavior of the collapse remain incompletely understood. In this study, we use broadband seismic waveforms recorded by the Agency for Meteorology, Climatology, and Geophysics (BMKG) network and apply the LS-FORCE single-force inversion framework to reconstruct the dynamic source process of the collapse. The inversion resolves three-dimensional force-time functions, force-vector orientations, and center-of-mass trajectories of the moving mass. Results reveal a dominant southwestward-directed collapse characterized by peak force amplitudes of approximately $8-9 \times 10^{11}$ N and a principal acceleration phase lasting about 20–30 s. Trajectory reconstruction indicates an effective moving mass of approximately 9.47×10^{10} kg and a runout distance of about 10 km, consistent with independent geological, geodetic, and remote-sensing observations. Comparison with previous seismic studies confirms the inferred collapse direction and tsunami-generation mechanism while providing new constraints on the temporal evolution of force release and collapse kinematics. These findings demonstrate that long-period seismic observations contain sufficient information not only to detect collapses but also to quantify their dynamics. The results highlight the potential of force-based seismic inversion as a rapid characterization tool for volcanic landslides and other tsunamigenic mass movements, contributing to the development of near-field multi-source tsunami warning systems.

1. Introduction

On 22 December 2018, a catastrophic flank collapse of Anak Krakatau volcano in the Sunda Strait, Indonesia, generated a destructive tsunami that struck the coastlines of western Java and southern Sumatra, causing more than 430 fatalities and widespread damage [1,2]. Unlike most tsunamis in Indonesia, which are triggered by large tectonic earthquakes, the Anak Krakatau tsunami occurred without a preceding earthquake that could be rapidly detected by conventional tsunami warning systems [3]. Subsequent field surveys, satellite observations, and tsunami modeling demonstrated that the tsunami was generated by the rapid collapse of the volcano's southwestern flank into the sea [1,2,4]. The event highlighted the vulnerability of densely populated coastal regions to volcano-induced tsunamis and emphasized the need for monitoring approaches capable of rapidly detecting non-tectonic tsunami sources [5,6].

Anak Krakatau is an active volcanic island located within the Sunda Strait between Java and Sumatra (Fig. 1), along the Sunda Arc formed by the subduction of the Indo-Australian Plate beneath the Eurasian Plate [7,8]. The volcano emerged in 1927–1928 within the caldera formed by the catastrophic 1883 Krakatau eruption and has since experienced persistent eruptive activity. Rapid volcanic growth, repeated lava emplacement, and the development of steep submarine slopes contributed to long-term instability of the volcanic edifice [8]. Satellite geodetic observations revealed progressive deformation of the southwestern flank prior to the 2018 collapse [4,8], while intensified eruptive activity during mid-2018 likely increased the gravitational loading of the unstable sector.

Previous studies have significantly improved our understanding of the 2018 collapse and tsunami. Satellite imagery and geodetic analyses identified the geometry and volume of the collapsed flank, while tsunami simulations demonstrated that the landslide

was capable of generating the observed tsunami heights and arrival times [2,4]. Seismological investigations further showed that the event generated strong long-period seismic signals but weak high-frequency body waves [2], distinguishing it from ordinary tectonic earthquakes. Single-force inversions and long-period waveform analyses have constrained the overall collapse direction and source duration, whereas more recent studies have explored rapid seismic detection and location techniques for operational tsunami warning [2,3,9,10]. Nevertheless, the detailed time evolution of the collapse force, the dynamic trajectory of the moving mass, and their implications for rapid characterization of tsunami sources remain incompletely understood.

In this study, we apply the LS-FORCE single-force inversion framework to long-period seismic waveforms recorded by the BMKG broadband seismic network to reconstruct the force history and kinematic evolution of the 22 December 2018 Anak Krakatau flank collapse. The inversion reveals a dominant southwestward-directed collapse characterized by peak force amplitudes on the order of 10^{12} N, an effective moving mass of approximately 9.5×10^{10} kg, and a runout distance of about 10 km. These results provide new insights into the dynamics of the collapse and demonstrate the potential of long-period seismic observations for rapid characterization of volcanic landslides and near-field multi-source tsunami warning.

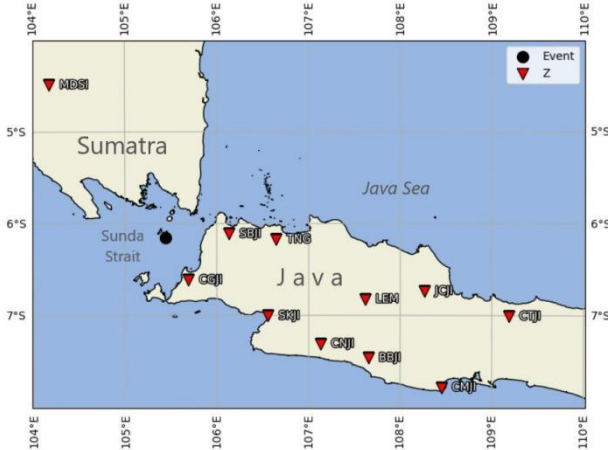


Fig. 1: Location of Anak Krakatau volcano (black dot) and distribution of selected seismic stations (red inverted triangles) used in this study

2. Data and Method

2.1 Seismic Data

This study utilizes broadband seismic waveform data recorded by the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) seismic network during the 22 December 2018 Anak Krakatau flank collapse. The BMKG network consists of permanent broadband stations distributed across Sumatra, Java, and surrounding regions, providing good azimuthal coverage of the Sunda Strait (Fig. 1). Of the 30 seismic stations located within 500 km of

the source, we selected 11 stations with high signal-to-noise ratios ($\text{SNR} > 5$) and clear long-period surface-wave arrivals associated with the collapse event (Table 1; Fig. 2). Instrument responses were removed from the waveform data, and the records were converted to ground displacement (Fig. 2). Following previous studies of large landslides and volcanic flank collapses, the analysis focused on long-period (8-125 s) seismic signals [2], which are more sensitive to the bulk motion of large masses than to high-frequency processes associated with brittle failure. The waveform data were bandpass filtered between 8 and 125 s to emphasize the long-period surface-wave signals generated by the bulk motion of the collapsing volcanic flank. The processed waveforms were subsequently used as input for the LS-FORCE inversion framework.

2.2 LS-FORCE Inversion Framework

The source process was modeled using LS-FORCE, a Python-based single-force inversion framework developed by Toney and Allstadt [11] for investigating large landslides and other mass-movement events. The method represents a landslide source as a time-dependent equivalent force acting on the Earth, where the force corresponds to the reaction force generated by acceleration of the moving mass. Unlike conventional earthquake source inversions that solve for moment tensors, LS-FORCE directly estimates the three-dimensional force history associated with the center-of-mass motion of the landslide. This approach is particularly suitable for volcanic flank collapses and tsunamigenic landslides, which often radiate strong long-period surface waves but weak body-wave energy [2].

The relationship between the model and the observations can be expressed through the following forward equation [11]:

$$\mathbf{d} = \mathbf{G}\mathbf{f} \quad (1)$$

Here, $\mathbf{d}$ denotes a single column vector formed by stringing together, one after another, every channel of recorded ground motion: $\mathbf{d} = [u^1, u^2, \dots, u^k, \dots, u^M]^T$ (the raised T indicates a matrix transpose). Since each channel shares the same sampling rate and record length, p , the overall size of this vector works out to $\text{length}(\mathbf{d}) = Mp$. Meanwhile, $\mathbf{f}$ stands for the unknown force history being solved for, assembled by joining its vertical, north, and east components end to end: $\mathbf{f} = [f^Z, f^N, f^E]^T$. Its total size is thus $\text{length}(\mathbf{f}) = 3q$, where q gives the sample count within a single force component.

The unknown $\mathbf{f}$ can then be recovered by solving a least-squares inversion that applies higher-order Tikhonov regularization, following the approach described by Toney and Allstadt [11]:

$$\mathbf{f} = [\hat{\mathbf{G}}^T \hat{\mathbf{G}} + \alpha^2 (r_0 \mathbf{I} + r_1 \mathbf{L}_1^T \mathbf{L}_1 + r_2 \mathbf{L}_2^T \mathbf{L}_2)]^{-1} \hat{\mathbf{G}}^T \hat{\mathbf{d}} \quad (2)$$

Here I represents the identity matrix, while L_1 and L_2 act as roughening operators of first and second order, standing in for approximations of the first and second derivatives. Weighting among these terms is set by three coefficients, r_0 , r_1 , and r_2 , together called tikhonov ratios, which respectively determine how strongly the solution is pushed toward being “small,” “flat,” or “smooth.” These three weights must together add up to unity: $\sum_{i=0}^2 r_i = 1$. The degree of regularization is governed by the trade-off parameter α , which is determined using the L-curve criterion (Fig. 3).

The inversion procedure begins with the computation of Green’s functions between the source region and each seismic station using the IASP91 Earth velocity model. The IASP91 velocity model was selected because it is a widely used global reference model and provides a practical and consistent representation of the Earth’s structure for regional waveform inversion and potential operational implementation. The observed seismic waveforms are then related to the unknown force-time functions through a linear inverse problem [11]. LS-FORCE simultaneously solves for the three orthogonal force components (east, north, and vertical) as a function of time by minimizing the waveform misfit between observed and synthetic seismograms (Fig. 3, 4). To suppress instability and reduce the influence of noise, the inversion incorporates smoothing and regularization constraints that favor physically realistic force histories [11].

Table 1: List of seismic stations used in this study

No.	Code	Lon. (°)	Lat. (°)	Distance (km)
1.	CGJI	105.6900	-6.6134	58.2
2.	SBJI	106.1318	-6.1117	76.7
3.	TNG	106.6469	-6.1719	133.6
4.	SKJI	106.5563	-7.0053	155.5
5.	CNJI	107.1296	-7.3090	226.5
6.	MDSI	104.1783	-4.4861	231.1
7.	LEM	107.6143	-6.8232	251.8
8.	BBJI	107.6500	-7.4626	284.2
9.	JCJI	108.2631	-6.7344	318.9
10.	CMJI	108.4490	-7.7840	378.4
11.	CTJI	109.1836	-7.0075	424.7

To evaluate solution robustness, LS-FORCE employs a jackknife resampling approach in which multiple inversions are performed using different subsets of seismic stations [11, 12]. The resulting ensemble of force-time functions provides an estimate of model uncertainty and allows assessment of the stability of the inferred source characteristics. The preferred solution is obtained from the complete station set, while the distribution of jackknife solutions is used to quantify confidence in the recovered force amplitudes, orientations, and durations [11].

Following inversion, the recovered force-time functions can be integrated to reconstruct the kinematic evolution of the moving mass. Assuming a specified runout distance based on previous observations [4,8,13], LS-FORCE estimates the

effective moving mass and computes the corresponding velocity, displacement, and center-of-mass trajectory through time [11]. The resulting trajectory provides information on collapse direction, runout length, and vertical motion, enabling direct physical interpretation of the collapse process. For the Anak Krakatau event, the reconstructed force history and trajectory were subsequently analyzed to infer the dynamics of the flank collapse and their implications for tsunami generation and near-field tsunami warning.

3. Results and Discussions

3.1 Results of the Inversion

The LS-FORCE inversion reveals a coherent and stable force-time function (FTF) associated with the 22 December 2018 Anak Krakatau flank collapse (Fig. 5). The jackknife realizations show relatively small variability around the preferred solution, particularly during the main phase of the collapse, indicating that the inferred source process is robust and not strongly controlled by the selection of individual stations. A summary of the source parameters obtained from the inversion in this study is presented in Table 2.

All three force components remain close to zero before approximately 70–80 s, suggesting that little large-scale mass acceleration occurred during the early part of the analyzed time window. Beginning at approximately 80 s, the force vectors show a systematic departure from the background level and evolve into a pronounced pulse between 90 and 115 s. This interval represents the principal collapse phase and corresponds to the largest acceleration of the collapsing edifice.

The horizontal force components dominate the solution. The northward and eastward components both exhibit large positive peaks reaching approximately $6\text{--}7 \times 10^{11}$ N near 100 s, whereas the vertical component reaches only about $2\text{--}3 \times 10^{11}$ N. The substantially larger horizontal forces indicate that the collapse was characterized primarily by lateral motion rather than vertical subsidence, consistent with a large-scale sector failure of the volcanic flank.

The nearly synchronous positive peaks observed in both horizontal components imply a collapse trajectory directed toward the northeast quadrant. Because the force recovered by LS-FORCE represents the reaction force exerted on the Earth, the actual center-of-mass acceleration of the failed mass occurred in the opposite direction. Consequently, the inversion is consistent with a southwestward-moving mass, in agreement with geological and bathymetric evidence indicating failure of the southwestern flank of Anak Krakatau.

The force amplitude rapidly decreases after approximately 110 s, suggesting that the largest acceleration phase lasted only about 20–30 s. Following the main pulse, the force-time function displays several smaller oscillatory peaks between approximately 120 and 170 s. These secondary pulses likely reflect continued downslope transport,

interaction with the submarine environment, progressive disaggregation of the collapsing material, and deceleration of the moving mass rather than a separate major collapse episode.

The evolution of total force magnitude (Fig. 6) highlights the temporal development of the collapse process. Force amplitudes remain low during the first ~ 50 s of the inversion and then gradually increase to approximately $2\text{--}3 \times 10^{11}$ N by 70–80 s. This gradual increase likely reflects the onset of flank destabilization and progressive acceleration of the unstable sector.

The force magnitude subsequently rises sharply to a maximum of approximately $8\text{--}9 \times 10^{11}$ N at about 100 s. This peak represents the moment of maximum bulk acceleration of the collapsing mass and is interpreted as the primary failure stage. The sharp rise and fall of the force magnitude indicate a highly impulsive source process, consistent with catastrophic gravitational collapse rather than slow deformation.

After the principal peak, the force magnitude decreases rapidly but remains elevated for several tens of seconds. A secondary force increase is observed around 140 s, reaching approximately $3\text{--}4 \times 10^{11}$ N. Although significantly smaller than the main peak, this feature suggests that substantial mass motion continued after the initial collapse, potentially reflecting submarine runout, interaction with seafloor topography, or delayed failure of additional material. The persistence of measurable force amplitudes until approximately 170–180 s indicates that the complete collapse process lasted on the order of 100 s, considerably longer than the duration of the main acceleration pulse itself.

The inferred force azimuth provides important constraints on the directionality of the collapse (Fig. 6). During the pre-collapse interval the azimuth is poorly constrained because the force amplitudes are near zero. Once the collapse begins, however, the azimuth stabilizes and exhibits relatively coherent behavior.

Between approximately 20 and 85 s the force vector is directed toward azimuths of roughly $220\text{--}250^\circ$ clockwise from north. Near the onset of the main collapse pulse, the azimuth abruptly rotates and stabilizes around $40\text{--}60^\circ$. This direction coincides with the interval of maximum force amplitude and therefore represents the most reliable estimate of the dominant force orientation.

Because the force vector represents the reaction force applied to the Earth, the corresponding mass acceleration is directed approximately 180° opposite to the inferred force azimuth. The collapse trajectory therefore points toward approximately $220\text{--}240^\circ$, consistent with southwestward transport of material into the Sunda Strait. This directional estimate agrees remarkably well with independent observations showing that the southwestern flank of Anak Krakatau underwent catastrophic failure during the eruption.

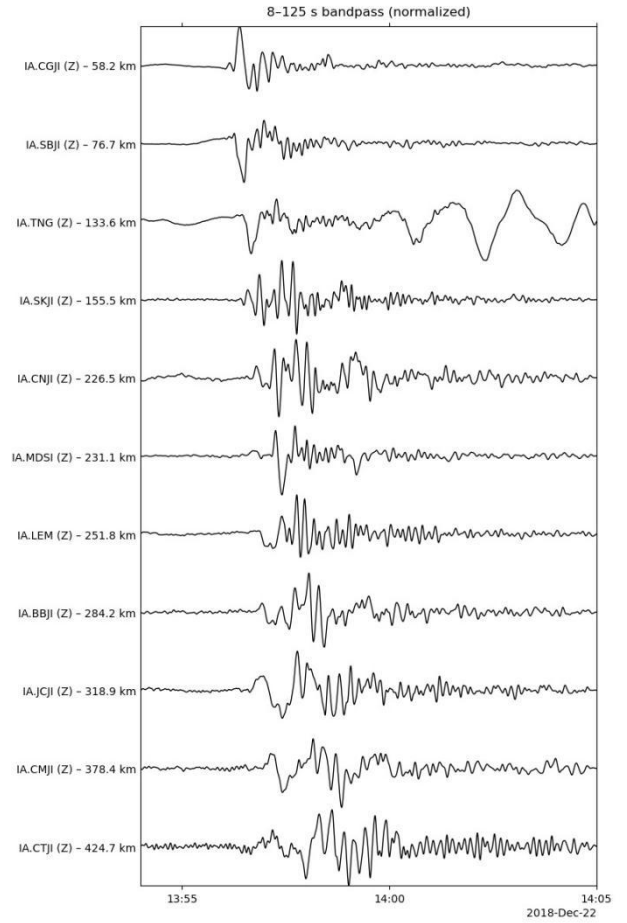


Fig. 2: Bandpass-filtered (8–125 s) displacement waveforms of the data, respectively. Z is vertical component of the seismic data. The station name and the distance are indicated on the left.

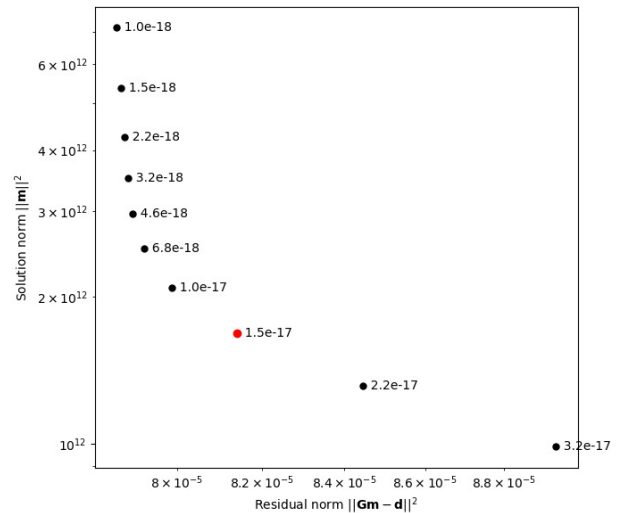


Fig. 3: The L-curve showing the residual norm versus solution norm for a range of tested trade-off parameter values (α). Numbers beside each point indicate the corresponding α value. The optimal solution is highlighted by the red dot, which corresponds to the point of highest curvature and represents the preferred compromise between model complexity and data fit.

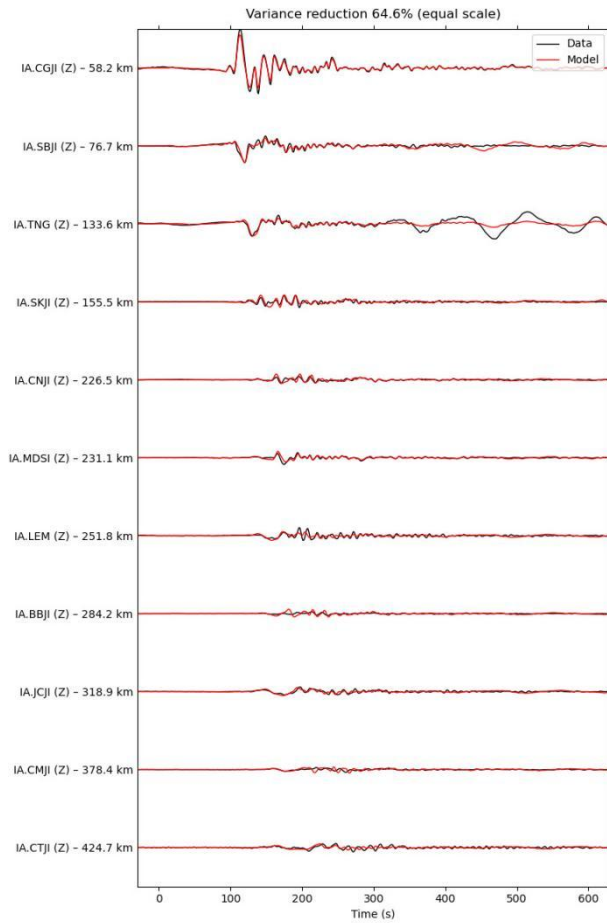


Fig. 4: Waveform fitting. Comparison of observed seismograms as input data (black) to modeled (synthetic) data (red).

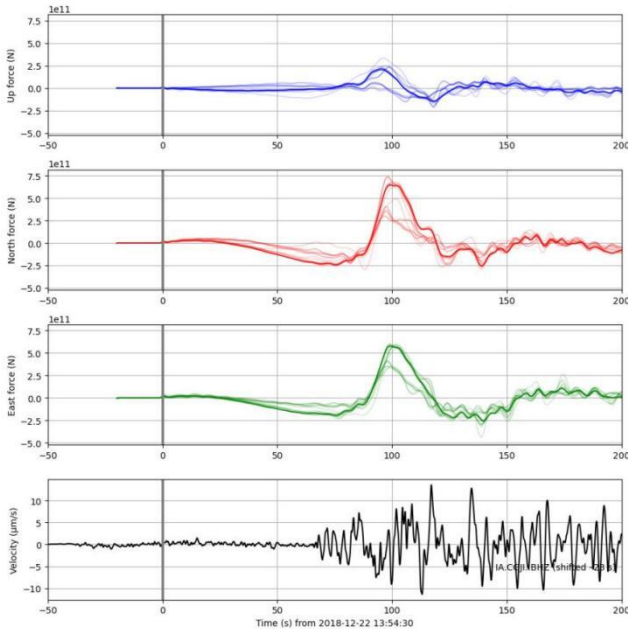


Fig. 5: LS-FORCE inversion results. Solid lines show the preferred force-time functions, while semi-transparent lines represent jackknife realizations. The black waveform shows the vertical component at station IA.CGJI, aligned using a 2.5 km s^{-1} surface-wave travel-time correction.

Table 2. Summary of the inversion results

Parameter	Result	Remarks
Peak total force	$\sim 8\text{--}9 \times 10^{11} \text{ N}$	Main collapse force
Main acceleration phase	$\sim 20\text{--}30 \text{ s}$	Principal acceleration
Significant force duration	$\sim 100 \text{ s}$	Including secondary pulses
Dominant collapse direction	Southwest	$\sim 220\text{--}240^\circ$
Effective moving mass	$9.47 \times 10^{10} \text{ kg}$	$\sim 94.7 \text{ Mt}$
Effective bulk volume	$\sim 0.04\text{--}0.06 \text{ km}^3$	For $1800\text{--}2500 \text{ kg m}^{-3}$
Target runout	$\sim 10 \text{ km}$	Observationally constrained
Horizontal displacement	$\sim 6\text{--}7 \text{ km W} + 7\text{--}8 \text{ km S}$	COM trajectory
Maximum downward displacement	$\sim 0.8\text{--}1.0 \text{ km}$	Less well constrained
Main force orientation	Reaction force NE	Corresponding mass motion SW

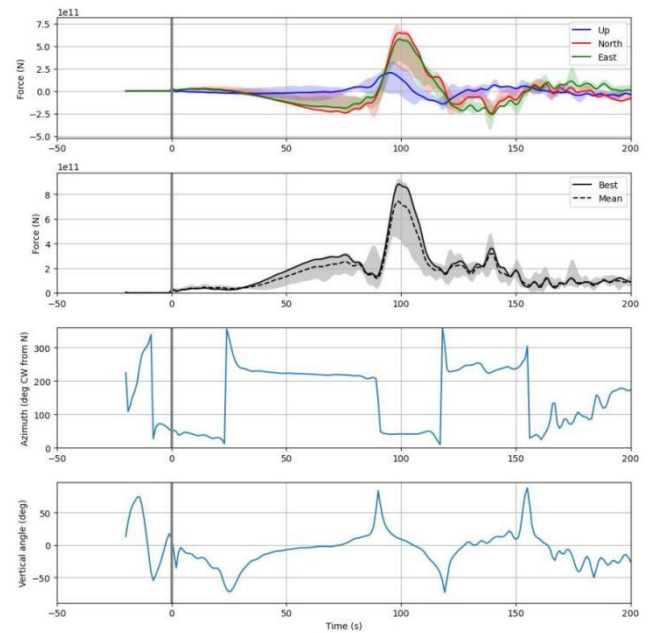


Fig. 6: LS-FORCE inversion results. The upper panel shows the recovered force-time functions, with shading indicating the range of solutions obtained from uncertainty analyses. The second panel presents the total force magnitude through time, whereas the third and fourth panels display the evolution of the force-vector azimuth and vertical angle, respectively.

The relative stability of the azimuth during the largest force pulse suggests that the collapse was dominated by a single preferential direction rather than a radially expanding or highly complex failure geometry. The temporal evolution of the force-vector inclination provides additional information about the geometry of the collapse. Prior to the main collapse phase, the vertical angle fluctuates substantially, reflecting the low signal amplitude and reduced directional stability.

During the main pulse, the vertical angle increases to approximately $+80^\circ$, indicating a significant upward component in the reaction force and therefore a strong downward acceleration of the collapsing mass. This behavior is expected during rapid gravitational failure when material transitions from the volcanic edifice onto the submarine slope.

Immediately following the main pulse, the vertical angle rapidly decreases and reaches values near -70° . This reversal suggests a change in the dominant acceleration regime, possibly associated with impact, deceleration, spreading, or interaction of the collapsing material with the submarine environment. After approximately 120 s, the vertical angle oscillates around near-horizontal values, indicating that the remaining motion was increasingly dominated by horizontal transport rather than major vertical acceleration.

Using the force-time function derived from the LS-FORCE inversion, we reconstructed the center-of-mass (COM) trajectory of the collapsing Anak Krakatau flank following the approach of Toney and Allstadt [11]. A target runout distance of 10 km was imposed during the trajectory inversion, yielding an estimated effective moving mass of approximately 9.47×10^{10} kg (94.7 Mt).

The reconstructed trajectory indicates a highly directional collapse toward the southwest sector of the volcano (Fig. 7). The preferred solution shows the COM moving from the source region near the volcanic edifice toward coordinates approximately 6–7 km west and 7–8 km south of the inferred source location. The overall trajectory length is approximately 10 km, consistent with the imposed runout constraint.

The ensemble of jackknife realizations displays relatively small dispersion during the first half of the trajectory, indicating that the initial collapse direction is well constrained by the seismic observations. Divergence among trajectories increases during the later stages of motion, reflecting the accumulation of uncertainty associated with double integration of the force-time function. Nevertheless, nearly all realizations indicate southwestward transport, demonstrating that the overall collapse direction is robust.

The reconstructed trajectory agrees with independent geological observations indicating failure of the southwestern flank of Anak Krakatau during the 22 December 2018 eruption. The seismic inversion therefore successfully captures the first-order geometry of the collapse despite relying exclusively on long-period seismic waveforms.

The color-coded trajectory provides insight into the temporal evolution of the collapse. During the first approximately 70–80 s, the center of mass exhibits only limited displacement, consistent with the relatively low force amplitudes observed in the force-time functions.

A pronounced increase in displacement rate occurs between approximately 80 and 120 s, coinciding with the interval of maximum force magnitude identified in the inversion. During this

period the trajectory rapidly advances southwestward, indicating that the majority of the total runout occurred during a relatively short interval. This behavior is characteristic of catastrophic gravitational collapse, in which most displacement occurs during a brief phase of rapid acceleration.

After approximately 120 s, the trajectory gradually flattens and displacement rates decrease, indicating progressive deceleration of the moving mass. This temporal evolution mirrors the decline in force magnitude following the main force pulse and suggests that the principal tsunami-generating stage was associated with the initial acceleration phase rather than the later stages of transport.

The concentration of displacement within a narrow time interval supports the interpretation that tsunami generation was driven primarily by rapid emplacement of a large volume of material into the surrounding marine environment.

The profile-view trajectory (Fig. 8) reveals the vertical evolution of the reconstructed center of mass during the collapse. During the initial stage, the COM remains close to its starting elevation, exhibiting only minor vertical displacement. Beginning at approximately 4–5 km of horizontal travel, the trajectory undergoes a pronounced downward excursion reaching approximately 0.8–1.0 km below the initial level. This phase corresponds closely to the interval of strongest downward acceleration inferred from the force-vector inclination analysis.

The downward motion is interpreted as the transition of the collapsing volcanic flank from the subaerial edifice into the submarine environment. Such behavior is consistent with the known morphology of Anak Krakatau, where the failed southwestern sector descended into the adjacent submarine slope.

Following the main descent phase, the trajectory gradually rises toward its final position. The preferred solution terminates slightly above the initial elevation, whereas the jackknife realizations span a range of approximately -1.5 to $+1.0$ km. This substantial spread indicates that the vertical component is less well constrained than the horizontal motion, a behavior also reported by Toney and Allstadt [11] for landslide trajectory inversions. Because vertical displacement results from double integration of the force-time function, small uncertainties in force amplitude can accumulate into significant trajectory differences. Consequently, the horizontal runout direction and distance are considered more reliable than the absolute vertical displacement values.

3.2 Consistency of our result with previous seismic studies

Several previous studies investigated the 22 December 2018 Anak Krakatau collapse using seismic observations, but they focused on different aspects of the source process. Walter et al. [4] combined seismic, InSAR, thermal, and satellite observations to identify

the collapse sequence and its precursory deformation, whereas Ye et al. [2] performed regional waveform inversion to estimate an equivalent single-force source. More recently, Permana et al. [9] examined the detectability of the collapse using regional seismic amplitudes, and Vera et al. [10] developed a long-period back-projection framework for rapid collapse detection and location.

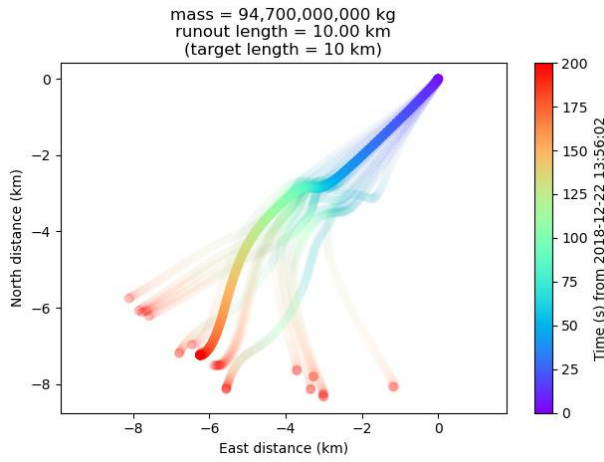


Fig. 7: Trajectory analysis. Map view of the 2018 Anak Krakatau flank collapse trajectory estimate for the inversion.

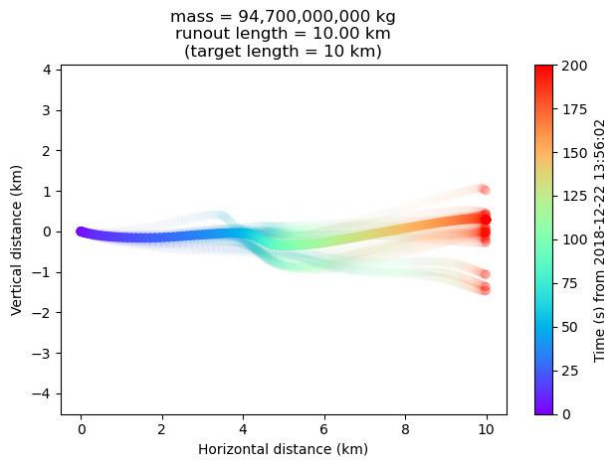


Fig. 8: Trajectory analysis. Cross-sectional view of the 2018 Anak Krakatau flank collapse trajectory estimate for the inversion.

Despite their different methodologies, all studies consistently identify the Anak Krakatau event as a long-period, landslide-dominated source characterized by weak body-wave radiation and unusually strong surface waves. Walter et al. and Ye et al. both emphasized the lack of strong high-frequency body waves, explaining why the event was not recognized by conventional earthquake-based tsunami warning systems [2,4]. Our inversion in this study independently reproduces these fundamental characteristics while additionally providing a time-dependent force history and a physically interpretable trajectory of the collapsing mass. Table 3 presents a comparison of the seismic models

obtained in this study with those from previous seismological studies.

Table 3. Comparison of the results of this study to previous seismic studies

Study	Main method	Main contribution	Main source information
Walter et al. (2019)	Seismic + InSAR + satellite/geodetic observations	Identified collapse geometry and precursory deformation	Southwestern flank failure
Ye et al. (2020)	Regional long-period waveform inversion	Estimated equivalent single-force source	Force $\sim 6.1 \times 10^{11}$ N; duration ~ 54 – 80 s
Permana et al. (2023)	Regional seismic amplitude/detectability analysis	Investigated rapid seismic recognition of collapse	Collapse-related seismic signatures
Vera et al. (2025)	Long-period back-projection	Rapid detection/location	Location in ~ 3 min
This study	LS-FORCE 3-D force-time inversion + trajectory reconstruction	Time-dependent force evolution and center-of-mass kinematics	Peak force 8 – 9×10^{11} N; ~ 100 s force history; southwestward trajectory; effective mass 9.47×10^{10} kg

3.3 Collapse direction and trajectory

One of the most robust findings from our inversion is the southwestward-directed collapse trajectory. The force azimuth during the main acceleration phase is approximately 40 – 60° , implying a reaction force directed northeastward and therefore a southwestward-moving landslide. This result agrees remarkably well with Ye et al. [2], who obtained a preferred single-force azimuth of 42° and interpreted it as the reaction force generated by a landslide moving down the southwest flank. Their preferred solution consisted of a northeastward-directed force dipping 12° upward with a peak force of approximately 6.1×10^{11} N. Similarly, Walter et al. used satellite observations and InSAR deformation measurements to demonstrate that the unstable sector was located on the southwestern flank and had been progressively moving westward prior to collapse [4].

The trajectory inversion presented here provides an additional level of information that was not available in previous seismic studies [2,4,9,10]. Rather than inferring collapse direction solely from force orientation or geomorphological observations, the LS-FORCE inversion reconstructs the center-of-mass motion itself [11]. The resulting southwestward

path is therefore independently consistent with both the single-force inversion of Ye et al. [2] and the satellite-based collapse geometry reported by Walter et al. [4].

3.4 Force magnitude and source characteristics

The peak total force magnitude obtained from our inversion reaches approximately $8\text{--}9 \times 10^{11}$ N, with the dominant contribution arising from the horizontal north and east components. Ye et al. [2] estimated a peak force of approximately 6.1×10^{11} N using a simplified single-force representation constrained to a prescribed source geometry. The somewhat larger peak force recovered by our model likely reflects methodological differences. The Ye et al.'s inversion assumed a parameterized force geometry and approximated the source as a single-force pulse [2]. In contrast, LS-FORCE model in this study allows recovery of a more flexible force-time history and resolves force evolution independently in three dimensions [11]. Consequently, the inversion captures secondary accelerations and directional changes that may not be represented by a single sinusoidal pulse.

Despite these differences, both studies converge on the same order of magnitude (10^{11} N), indicating that the Anak Krakatau collapse generated force amplitudes typical of large but not exceptional landslides. This observation is consistent with Ye et al. [2], who noted that the force amplitude lies near the middle of the global distribution of seismically observed landslides.

3.5 Duration and collapse dynamics

An important distinction between our results and previous studies concerns the duration of the collapse process. Ye et al. [2] initially obtained a one-cycle force pulse with a duration of approximately 54 s from regional waveform inversion. Subsequent deconvolution yielded a more complex force-time history lasting approximately 80 s and consisting of a leading positive pulse followed by a broader deceleration phase [2]. The LS-FORCE inversion in this study indicates that significant force release persisted for roughly 100 s, although the principal acceleration phase occurred over only 20–30 s near the force maximum. The longer duration inferred from LS-FORCE model arises from the presence of several secondary force pulses after the main collapse. These secondary pulses may represent progressive disintegration of the collapsing flank, continued submarine transport, interaction with submarine topography, or sequential failures of unstable material.

This interpretation is broadly consistent with Permana et al. [9], who suggested that the seismic record contains evidence for multiple collapse-related signals and complex eruptive activity during the collapse sequence rather than a single instantaneous failure. Therefore, our results support a model in which the Anak Krakatau collapse was a multi-stage process characterized by a short interval

of catastrophic acceleration followed by continued downslope mass transport.

3.6 Runout distance and effective mass

Using a 10 km target runout, the LS-FORCE trajectory inversion yields an effective moving mass of approximately 9.47×10^{10} kg. This value corresponds to a bulk volume on the order of 0.04–0.06 km³ for typical volcanic rock densities of 1800–2500 kg m⁻³. The estimate falls within the broad range proposed by previous studies. Williams et al. estimated ~ 0.004 km³ subaerial collapse [13]. Ye et al. suggested the total volume was likely <0.2 km³ [2]. Gouhier and Paris estimated approximately 0.094 km³ [14]. Early tsunami scenarios considered collapse volumes up to 0.28 km³. The agreement indicates that the effective mass inferred from inversion in this study is physically reasonable and consistent with independent geological and remote-sensing constraints.

3.7 Implications for tsunami generation

Previous studies generally agree that the tsunami was generated primarily by flank collapse rather than by a tectonic earthquake. Walter et al. [4] identified the collapse as the culmination of a prolonged period of volcanic growth and flank instability. Ye et al. [2] demonstrated that a relatively small landslide (<0.2 km³) could nevertheless generate a destructive tsunami because of the rapid acceleration of the failing mass. They argued that source geometry, force amplitude, and source duration could be used as the basis for future tsunami warnings [2, 15, 16, 17, 18]. Our model results strengthen this interpretation. The force-time history indicates that the majority of momentum transfer occurred during a brief interval centered around the force maximum. Although collapse-related motion persisted for nearly 100 s, the strongest water displacement was probably associated with the short-lived high-acceleration stage. This finding suggests that tsunami generation depends more strongly on the acceleration history of the collapse than on the total collapse duration. The force peak therefore represents a potentially valuable proxy for estimating tsunami-generating efficiency directly from seismic observations.

3.8 Implications for near-field tsunami warning

Perhaps the most important advance relative to previous studies is the potential operational value of the LS-FORCE inversion. Ye et al. [2] demonstrated that regional long-period waveform inversions could characterize the collapse within approximately 8–10 minutes after occurrence. Permana et al. [9] proposed an amplitude-based regional monitoring strategy capable of recognizing collapse-related seismic signatures that are missed by conventional earthquake detection algorithms. Vera et al. [10] subsequently showed that long-period back-projection can locate the Anak Krakatau collapse within approximately 3 minutes of initiation using the existing Indonesian broadband network.

Taken together with our results, these studies suggest a possible operational workflow:

- a) Rapid long-period detection and location;
- b) Automatic discrimination of landslide versus earthquake sources;
- c) Real-time LS-FORCE inversion to estimate force magnitude, collapse direction, duration, and trajectory; and
- d) Physics-based tsunami forecasting using the inferred source parameters.

Under such a framework, the southwestward-directed trajectory, peak force of $\sim 10^{12}$ N, and force duration of ~ 100 s could potentially be estimated before the arrival of the tsunami at many coastlines around the Sunda Strait, providing critical information for near-field multi-source tsunami warning systems.

Indonesia is located within one of the most tectonically and volcanically active regions in the world, where the interaction of the Indo-Australian, Eurasian, Pacific, and Philippine Sea plates has produced numerous active volcanoes, steep volcanic edifices, and complex submarine topography. Consequently, the country is highly susceptible not only to earthquake-generated tsunamis but also to volcanic flank collapses, submarine landslides, pyroclastic flows entering the sea, and other non-seismic tsunami sources [19, 20, 21, 22], highlighting the urgent need for a near-field multi-source tsunami warning system capable of rapidly identifying and characterizing diverse tsunami-generating processes [3].

Overall, the LS-FORCE inversion not only confirms the southwest flank-collapse interpretation established by previous studies but also extends it by providing a time-dependent reconstruction of force evolution and center-of-mass trajectory, parameters that are directly relevant for real-time characterization of tsunamigenic volcanic landslides. The principal advance of this study is the joint reconstruction of the time-dependent three-component force history and center-of-mass trajectory, providing constraints on temporal force evolution and three-dimensional collapse kinematics beyond those obtainable from simplified single-force or conventional earthquake source inversions. The applicability of LS-FORCE is expected to decrease for smaller collapses with weak long-period radiation, sparse or strongly asymmetric seismic networks, low-SNR observations, and complex multi-stage or multi-source failures that cannot be adequately represented by a single equivalent force history.

4. Conclusions

This study demonstrates the capability of long-period seismic waveform inversion to reconstruct the dynamics of the 22 December 2018 Anak Krakatau flank collapse and to provide valuable information for rapid characterization of non-seismic tsunami sources. Using the LS-FORCE inversion framework and broadband seismic data from the BMKG network, we recovered a coherent force-time history

characterized by dominant horizontal force components, a peak force magnitude of approximately $8\text{--}9 \times 10^{11}$ N, and a principal acceleration phase lasting about 20–30 s. The reconstructed center-of-mass trajectory indicates a southwestward-directed collapse with an effective moving mass of approximately 9.47×10^{10} kg and a runout distance of about 10 km, consistent with independent geological, geodetic, and remote-sensing observations. Comparison with previous seismic studies confirms the overall interpretation of a southwest flank failure as the primary source of the tsunami, while the LS-FORCE inversion provides additional constraints on the temporal evolution of force release and collapse kinematics. These results highlight that long-period seismic observations contain sufficient information not only to detect and locate volcanic landslides but also to quantify their dynamics in near real time. Consequently, the integration of force-based seismic inversion into operational monitoring systems could significantly enhance the rapid assessment of volcanic flank collapses and other tsunamigenic mass movements, contributing to more effective near-field multi-source tsunami warning strategies in Indonesia and other volcanically active coastal regions.

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