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Reply to: On the use of seismic noise studies for landslide rock block hazard assessment

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REPLYING TO Bottelin et al. *Communications Earth & Environment* https://doi.org/10.1038/s43247-026-04029-2 (2026)

In the matters arising "*On the use of seismic noise studies for landslide rock block hazard assessment*" by Bottelin P., Baillet L., and Larose E.[1], authors report some possible limitations about the methodology and conclusions provided in the paper "*Fast estimation of landslide blocks' volume from seismic noise measurements*," Communications Earth Environment (2025), https://doi.org/10.1038/s43247-025-02999-3 by Pazzi V., Fornasari S.F., Devoto S., Costa G., and Forte E.[2]. This reply is intended to address the main concerns raised in the matters arising by Bottelin et al.[1] to more clearly describe the use of fixed boundary conditions adopted in ref. 2, to underline limitations in the approach, and to discuss how alternative boundary conditions and block geometries might influence the system's dynamics (see the Session "Numerical simulation limitations"). Moreover, this reply addresses those concerns related to the identification of resonance frequencies from seismic noise data used in Pazzi et al.[2] to estimate the order of magnitude of the blocks' volume at the two test sites (see Section "Experimental methods limitations"). Therefore, this document does not provide any new quantitative evidence nor new independent validations beyond those already presented in the original study[2]. Finally, it is important to reiterate that the abacus proposed by Pazzi et al.[2] is strictly site-dependent and provides order-of-magnitude estimates of the blocks' volume. This is a core constraint in its use, because it is primarily intended for applications within a given geological setting, rather than as a generally transferable tool. Nonetheless, the procedure proposed by Pazzi et al.[2] can be used in a different geological context after developing a new site-dependent abacus implemented considering the proper geophysical and rheological parameters of the site.

Numerical simulation limitations

The use of seismic noise to investigate unstable rock slopes is innovative and promising[3], but still under development and not yet widely established in engineering geology. The problem is inherently complex, and simplifying assumptions both on the material properties and on the boundary conditions (e.g., degrees of freedom) are unavoidable when simulations are performed. In particular, when the geological and structural setting is like the one presented in Pazzi et al.[2], i.e., a setting in which a layer is softer than the overlying one, the latter can be modelled considering it resting on the underlying layer (boundary condition 1 - bc1) or being partially embedded in it (boundary condition 2 - bc2).

With direct reference to the geological conditions of the case studies illustrated[2], direct field observations and independent GPR surveys constrained blocks' thicknesses and identified basal contacts (e.g., Figure 7 in ref. 4), indicating that deeply embedded blocks are uncommon. On the other hand, the smallest blocks do not rest directly on clay but overlie other limestone blocks, as documented in Figures 3 and 4 in ref. 2 and in the supplementary material of Pazzi et al.[2]. The conceptual illustration in Figure 11 in ref. 4 is intended solely to convey the relative kinematics among blocks and should not be read as an actual cross-section of basal contact conditions. Therefore, for the case study[2], bc1 is the most plausible boundary condition.

When a block rests on the underlying layer, it can be modelled either assuming a fixed-base condition (bc1.1) between the two layers, as in Pazzi et al.[2] or as condition (i) in Bottelin et al.[1], or assuming a not fixed-base condition (bc1.2), as simulated under condition (ii) in Bottelin et al.[1]. The results of the simulations (panels a-d of Figure 1 in Bottelin et al.[1] and what is written in the text about a 20x20x10 m^3 block) highlight a difference in the resonance frequencies obtained for bc1.1 and bc1.2. In particular, when the block doesn't have a fixed boundary condition (bc1.2), it shows a lower resonance frequency. Field data[2] identify values of the resonance frequencies more similar to bc1.1 (fixed-base condition) than to bc1.2 (not fixed-base condition), thus supporting the choice carried out[2] to implement the eigenfrequency-volume abacus.

In case of a block partially embedded in the softer layer (bc2), as also shown by the outputs of the simulations[1], the embedded portion could also be affected by displacements (see panel f of Fig. 1[1]). Therefore, it is not correct to state that a block partially embedded in a softer substrate is free to move only in its emerged part, or to say that only the emerged part contributes to the definition of the eigenfrequency (as it seems assessed by comparing the simulations' results of blocks with the same height for the emerged part, but a different total height[1]). Indeed, for a partially embedded block, the eigenfrequency is related to the volume obtained by the sum of the emerging part plus a percentage of the embedded one (see Table 1). This percentage is linked to the geometrical factor of the block (as also shown by the results of the simulation[1]). It is out of the scope of this reply to quantify this contribution.

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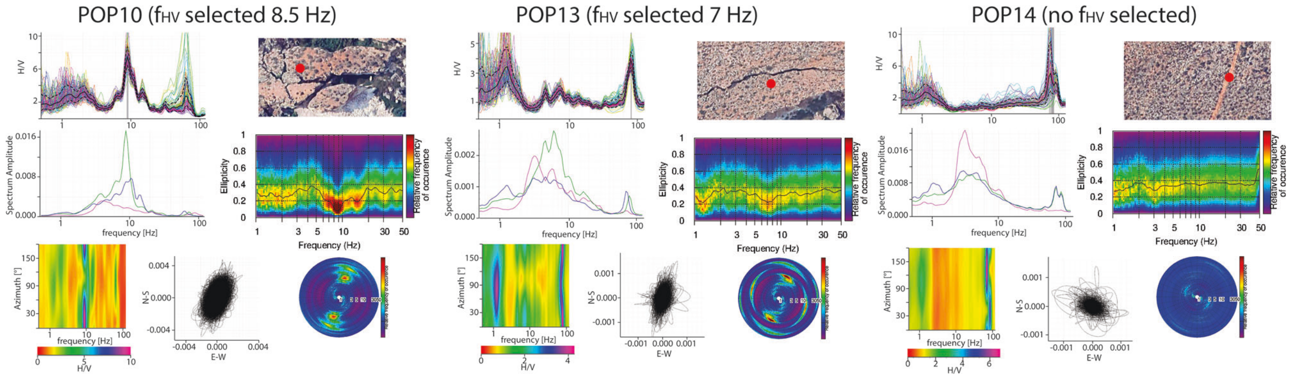

Fig. 1 | Features analysed to identify the block's representative frequency. For three different acquisitions (POP10, POP13, and POP14), H/V curves, three-component spectra, directivity, particle motion, strike, ellipticity, and measuring location [Photograph credit: Stefano Devoto (Units)] are shown (counterclockwise from the top left corner). POP10 has a clear H/V peak at the selected frequency; POP13 shows a H/V peak lower than 2 at the selected frequency, while POP14 does not show any selectable frequencies because it was acquired on the plateau (i.e., on an "infinite" volume).

Table 1 | Comparison between blocks' volume estimations

Simulated block's dimensions [m][1]	Real simulated block's dimensions [m]	Block's area [m^2]	Block's volume [m^3][1]	Real block's volume [m^3] (V_{calc})	Frequency [Hz] from simulation[1]	Volume [m^3] estimated (V_{est}) from abacus	Height [m] estimated (h_{est}) from the results of the abacus
10x10x10	10x10x(10 + 10)	100	1000	2000	7.69	1500	15
5x5x20	5x5x(20 + 10)	25	500	750	1.96	550	22

In the first two columns, the dimensions of the blocks simulated by Bottelin et al.[1] are reported, highlighting, in the second column, the quantity in brackets as the height considering both the emerged and the embedded portions of the block. The third column is the block's area, while the fourth and the fifth ones are the volume estimated using the dimensions in the first two columns, respectively. The sixth column is the frequency obtained by the simulation carried out by Bottelin et al.[1], while the seventh and the eighth are the volume and the height, respectively, obtained from the abacus.

However, as shown in Table 1, the volumes and the blocks' heights obtained from the abacus using the outputs of the numerical modal analyses[1] show intermediate values between those considering or not considering the embedded part.

The bc2 condition could also be applied to model non-isolated blocks constrained at the base to adjacent blocks: in such cases, the eigenfrequencies will be linked to the volumes free to vibrate and not to the whole blocks' volume. One might argue that the difference between the real block's volume (V_{calc}) and that estimated from the abacus (V_{est}) is an error arising from the application of the abacus built for bc1 to a bc2 setting. However, as stated at the end of the "Discussion: how to use the block's volume abacus" section[2], this difference could be used as a proxy to identify embedded or non-isolated blocks. Thus, the simplified assumption[2] of a fixed-base condition (bc1.1) to build the eigenfrequency-volume abacus is a realistic approximation, also for partially sunken or non-isolated blocks.

Experimental measurement limitations

Kleinbrod et al.[3] classify sites as depth-controlled or volume-controlled sites. In Figure 16 in ref. 3, the authors present the relationship between eigenfrequency and volume for 18 selected sites. The general trend indicates that, as expected, increasing volumes correspond to decreasing frequencies, with additional variability associated with the rheological properties of each site. Furthermore, Figure 17 in ref. 3 shows that the H/V curves recorded at (a) reference (stable) stations, and (d) depth-controlled sites are clearly distinct from those obtained at volume-controlled sites (b), highlighting their greatly different dynamic responses. Based on these results and having in mind that in literature the simplest way to obtain the eigenfrequency (f_0) of a block is to consider the stiffness and the mass (see eq. 1[2]) but that it is difficult to directly estimate $f_0$in the field, Pazzi et al.[2] proposed to use as a proxy for f_0 a frequency obtained from the analysis of seismic noise data called f_{HV}.

However, it should be noted that f_{HV}[2] is not the frequency of the highest peak in the H/V curve (i.e., the site's fundamental resonance frequency as intended by Bottelin et al.[1] in the supplementary material), which would be identified by applying the SESAME project criteria[5]. In fact, such criteria were developed specifically for 1D stratigraphic settings, which are not representative of isolated, 3D blocks' structures where the resonance is governed by geometric and mechanical boundary conditions. Therefore, the peaks' identification proposed[2] does not rely on the quality-control framework proposed by the SESAME project[5], and the reliability cannot be assessed by applying the SESAME guidelines alone. The procedure proposed[2] explicitly requires the combined evaluation of different indicators like the full three-component spectra, the directivity, and the polarisation analysis for all the acquired data, followed by integrated interpretation to distinguish frequencies attributable to regional stratigraphy, external noise sources, and block eigenfrequencies. Further details are provided in the next section.

Recommendations to identify a reliable f_{HV} from seismic noise data collected in volume-controlled sites

As mentioned above, the procedure proposed[2] to identify f_{HV} as a proxy of the block eigenfrequency f_0 requires integrated analyses on the H/V curve, the full three-component spectra, the directivity, and the polarisation. It is not possible to define a quantitative weight to give to the different indicators, but it is possible to outline the step-by-step order of the analysis, as follows:

1. The H/V curve, the three-component spectra, and the directivity of each acquisition have to be calculated.
2. All the H/V curves must be examined to identify stratigraphic peaks that should have roughly the same frequency, satisfy the SESAME criteria, be characterised by the well-known "eyes-shaped" behaviour of the three-component spectra, and not be affected by a preferential direction: plotting all the curves on the same graph will help this analysis.
3. Plotting all the H/V curves on the same graph will also help in identifying the range of frequencies f_{HV} that are linked to the volume of different blocks. These frequencies can or cannot show a H/V peak, because of the spectra of the vertical component that can be flat or can have the same behaviour of the horizontal spectra. This range of f_{HV} is the one to focus on in the further steps. It is important to note that even

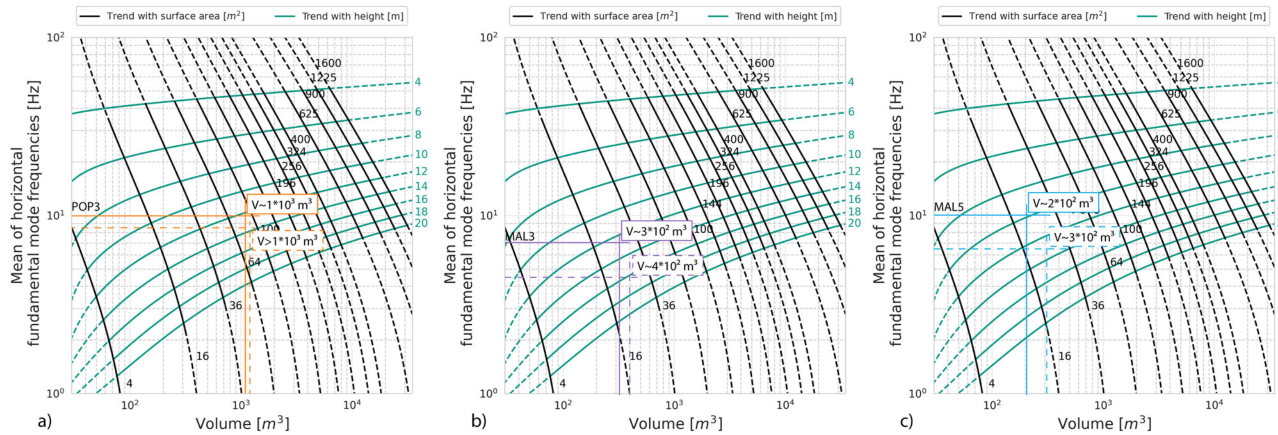

Fig. 2 | Comparison of the volumes estimated using the abacus. For three different blocks, a) POP3, b) MAL3, and c) MAL5, the volume was estimated using both the frequency reported in Pazzi et al.[2] (solid lines) and that reported in Bottelin et al.[1] (dashed lines). For each block, the order of magnitude of the volume is consistent, indicating that, in the range of frequencies of interest of this work, a variation up to 2 Hz of the fundamental frequency does not substantially impact the order of magnitude of the estimated volumes.

if numerical simulations shown[1] have a clear peak in the H/V spectrum, not all the field data can show this behaviour because, as reported in literature (e.g., ref. 3), the eigenfrequency can show an amplification of the vertical component, and thus a weak or poorly defined H/V peak.

4. The polarisation analysis has to be carried out for all the data in the frequency range selected in step 3;
5. For each measurement point, the frequency f_{HV} is identified by its polarisation, normal to the dominant fracture network, and by the near-zero ellipticity at that frequency, consistent with eigenvalue behaviour reported in the literature[2].

Figure 1 shows the H/V curve, the three-component spectra, the directivity, the particle motion, and the polarisation analysis (i.e., ellipticity and strike[6]) for three different sets of measurements[7]. For the three cases, the stratigraphic peak is always in the 1-2 Hz range, as reported in literature (see Table 4[2]). POP14 is acquired on the plateau and in the range 4-12 Hz does not show any of the volume-controlled frequencies. POP10 shows a clear peak in the H/V spectrum at the selected frequency, while POP13 has a H/V peak amplitude of around 2 at the selected frequency. Nevertheless, both sites show all the other indicators listed before and needed to select them as the f_{HV} to enter the abacus.

Given the range of frequency of interest, as stated in Pazzi et al.[2], an error of 1-2 Hz in the identification of f_{HV} does not affect the estimation of the volume's magnitude order. Figure 2a-c shows a comparison of the estimated volumes obtained using the abacus for the blocks POP3, MAL3, and MAL5, respectively, using the frequencies reported in Pazzi et al.[2] (solid lines) and those identified in the Supplementary material of Bottelin et al.[1] (dashed lines). The results indicate that variations in the selection of the fundamental frequency do not substantially impact the order of magnitude of the estimated volumes. In general, using the frequencies selected by Bottelin et al.[1], the estimated volume is higher than that obtained using the frequencies estimated by Pazzi et al.[2] and higher than that obtained through independent measurements and listed in Table 1[2].

Conclusions

The assumption of fixed-boundary conditions to build the eigenfrequency-volume abacus proposed by Pazzi et al.[2] is supported by field observation.

The selection of the frequency (f_{HV}[2]) to use to enter the abacus is the most challenging step in the procedure: here, further guidance and detailed suggestions for identifying a reliable f_{HV} are provided. It is important to remember once again that f_{HV}[2] is not the frequency of the highest peak in the H/V curve, i.e., the site's fundamental resonance frequency[1], and thus it does not necessarily satisfy the quality-control framework of the SESAME criteria. While stratigraphic peaks are similar on all the measures collected in a specific geological area (i.e., in a depth-controlled site), those related to block eigenfrequency are variable in inverse proportion to the block volumes (i.e., they are volume-controlled). Specific analyses and criteria for distinguishing between the two are critically evaluated and applied. Further studies should extend this approach to include different geological and rheological backgrounds.

Data availability

Seismic noise data used here are the same of the main manuscript (https://doi.org/10.1038/s43247-025-02999-3) and can be downloaded from https://doi.org/10.5281/zenodo.17521125. These data cannot be used without citing the source (cite both the related research articles and the dataset itself).

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Author contributions

Conceptualization: V.P. and E.F.; design of the work, acquisition: V.P., E.F. and S.D.; analysis: V.P., E.F. and S.F.F.; data interpretation: all authors; visualization: V.P., S.F.F. and S.D.; writing first draft: V.P., E.F., S.F.F. and S.D.; revision: all authors; funding: E.F., S.D. and G.C.

Competing interests

The authors declare no competing interests.

Additional information

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