High-resolution P- and S-wavefield seismic investigations of a quick-clay site in southwest of Sweden

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Abstract
Seismic investigations were performed at a site in the southwest of Sweden where major quick-clay landslides have occurred in the past. Given the potential high risk of the area and the presence of medium infrastructures, the site posed a need for detailed investigations in a wide depth range and in high resolution. A high-fold seismic survey was designed and conducted along two profiles using a 1–2 m receiver and shot spacing in order to retrieve both P- and S-wavefield seismic images from vertical component data. The data were analysed by combining first-break traveltime tomography and surface-wave analysis as well as P- and S-wavefield reflection seismic imaging. Using the first breaks, P-wave velocity ($V_P$) models were estimated, indicating the bedrock topography along the profiles and the sediment characteristics. The S-wave velocity ($V_S$) models were estimated from the surface waves and indicated areas of low shear strength. Combined with $V_P$ and $V_S$ models, this permits the estimation of $V_P/V_S$, a parameter that can indicate areas with high water content, significant for the detection of quick clays and possible liquefaction issues. The results are integrated with the P- and S-wave reflection seismic images and compared with other geophysical investigations, such as magnetic and gravity data that were collected along the profiles.

KEYWORDS
landslide, reflection, S-wave, surface wave, tomography

INTRODUCTION
Landslides occurring at quick-clay sites are a significant geotechnical hazard in several northern countries, as proven by the several quick-clay landslides that have occurred in recent years in North America and northern Europe, and have caused fatalities, environmental damages and loss of infrastructures (e.g., Brooks & Crow, 2020; Choquette et al., 1987; Crawford, 1968; Grahn & Jaldell, 2017; Geertsema & Torrance, 2005; Gregersen, 1981; Kerr & Drew, 1968; Locat & Lefebvre, 1985; Locat et al., 2017; Long et al., 2019; Penna & Solberg, 2021; Persson, 2014; Rankka et al., 2004). Quick clays are water-saturated deposits of clayey- and silt-size particles, which during the past deglaciation were rich in salts because of their marine depositional environments. Their subsequent isostatic uplift starting at around 11 kyr ago has resulted in freshwater infiltration and the reduction of their salinity, which was originally responsible for the bonding between the clay particles (e.g., Kerr, 1963; Torrance, 1979). Their strength was, thus, reduced to extremely low values. As a consequence, these deposits become vulnerable to collapse (Helle et al., 2018) and may liquefy when exposed to relatively low stress fields (e.g. strong rainfall, erosion, human activities such as excavations or waste dumping). As quick clays can be present in populated areas and where infrastructure exists, their delineation and characterization are of
great importance for site developments and mitigation of possible geohazards.

In this work, we apply a combination of different seismic methods to characterize a site prone to quick-clay landslides, located near the city of Trollhättan in southwest Sweden (Figure 1a). The site was chosen due to its vicinity to the area where, in 1957, a large quick-clay landslide occurred by the Göta river (Figure 1), causing fatalities, major loss of infrastructure and water contamination (Odenstad, 1958). It is located close to moderate infrastructures (Figure 1b), such as a windmill built on top of a hill, which could potentially be in risk in case of...
a landslide; hence, this work also was motivated to estimate the thickness of the soil under which the windmill was sited.

**PREVIOUS STUDIES**

Previous studies at the location of the 1957 quick-clay landslide and nearby areas alongside the Götå River have shown that different geophysical tools can successfully detect quick clays and improve the understating of their depositional environment (e.g., Dahlin et al., 2013; Malehmir, Bastani, et al., 2013; Malehmir, Saleem, et al., 2013; Pertuz & Malehmir, 2023; Salas-Romero et al., 2019; Wang et al., 2016; With et al., 2022). Techniques, which are popular for landslide characterization (e.g., electrical resistivity, ground-penetrating radar), might be ineffective for quick-clay studies because of their high conductivity setting that limits adequate investigation depths (e.g., Sauvin et al., 2014). A fully integrated method, utilizing also high-resolution seismic methods can be a solution (Malehmir, 2019, 2021), as seismic methods have proven effective in these types of settings and can provide a wealth of information crucial for a comprehensive characterization of quick-clay sites (e.g., Aylsworth & Hunter, 2004; Pugin et al., 2013).

It has been shown that environments where quick clays are present typically show a P-wave velocity \( V_P \) on the order of 1400–1500 m/s (Salas-Romero et al., 2016), whereas their S-wave velocity \( V_S \), reflecting the shear strength of the solid skeleton only, is expected to reach values as low as 50–100 m/s (e.g., Comina et al., 2017; Donohue et al., 2012; Pasquet et al., 2014; Sauvin et al., 2014). This is due to their water content, forcing them to act nearly like fluids. Therefore, the near-surface velocities and, mainly, the \( V_P/V_S \) (or equivalently the Poisson’s ratio) can serve as indicators of quick-clay presence or areas with extremely high water content. Moreover, they can be used to estimate the thickness of the sediments and provide crucial information on the geotechnical characteristics of the site, such as consolidation, shear strength, saturation and water content (L’Heureux & Long, 2017; Wang et al., 2016).

Seismic methods can also help to retrieve P- and S-wavefield reflections originated at the contact between the quick clay (or proxy horizons) and bedrock, which can be used to map the bedrock morphology (e.g., Krawczyk & Polom, 2018; Lundberg et al., 2014; Malehmir, Saleem, et al., 2013). In addition, possible layering of the quick clays can be imaged if there is sufficient contrast in terms of velocities and densities (e.g., Pertuz & Malehmir, 2023). Finally, due to the high \( V_P/V_S \), the clear separation of the P- and S-wavefields in the shot gathers can be expected and the retrieval of high-quality S-wave reflections even from vertical-component data should be possible. For instance, Malehmir (2019, 2021) used the data recorded by vertical-component geophones at a site close to the area investigated here and showed that high-quality, unaliased, S-wave arrivals (i.e., recorded with short shot and receiver spacing) can be retrieved from these data. The recording time should however be long enough to contain possible S-wavefield reflections in this extremely slow shear-velocity medium, and the spatial and temporal sampling parameters should be adequate for their retrieval. Under these conditions, S-wave reflections can be used to complement the reflections of P-waves, possibly allowing higher resolution imaging of the subsurface (Malehmir, 2019, 2021; Pertuz & Malehmir, 2023).

Motivated by these findings, two vertical-component type seismic profiles were acquired in 2021 in the study area in Trollhättan (Figure 1; P1 and P2). To optimize the S-wavefield retrieval, fine (1–2 m) shot and receiver spacing was used and high-fold common midpoint coverage (up to 200) was achieved. In this study, the data are used for both P- and S-wave reflection imaging and for near-surface \( V_P \), \( V_S \) and \( V_P/V_S \) estimations through a combination of first-break traveltome and surface-wave analysis.

**SEISMIC DATA ACQUISITION**

The parameters used for the seismic data acquisition are summarized in Table 1. A 5-kg sledgehammer was used as the seismic-energy source, generating three shot records at each shot point (in total 375 shot points along P1 and 268 shot points along P2). This was done to increase the signal-to-noise ratio by vertically stacking the repeated shot records during the processing stage. The data were recorded by 10-Hz vertical-component geophones connected to wireless recorders (Figure 1b), using a sampling rate of 1 ms and a record length of 10 s (reduced to 3 s for processing). The data were recorded in continuous mode, and the separate shots were subsequently isolated and extracted from the wireless recorders using the GPS times tagged for each shot. Along P1, 405 wireless units were deployed at a spacing of 1 m for the first 305 locations and 2 m for the remaining 100 stations. For P2, 275 wireless recorders at 1 m spacing were used. The elevation across P1 varies significantly (Figure 1), specially towards the NW, where the line crosses a steep hill, where the windmill (Figure 1) was located. Along P2, a steep slope was intersected towards the SE end, and, as a result, the line was interrupted before reaching the river.

**SEISMIC DATA QUALITY**

As an example of the data quality, a raw shot gather from P1 is shown in Figure 2a, where, despite some cultural noise in the data, first breaks can be distinguished for offsets up to 250 m, indicating near-surface
**TABLE 1** Main seismic data acquisition parameters of the seismic survey in Trollhättan, Sweden (2021).

<table>
<thead>
<tr>
<th>Survey parameters</th>
<th>Profile P1</th>
<th>Profile P2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recording system</td>
<td>Sercel Lite</td>
<td>Sercel Lite</td>
</tr>
<tr>
<td>Survey geometry</td>
<td>Fixed nodal</td>
<td>Fixed nodal</td>
</tr>
<tr>
<td>Source type</td>
<td>5-kg sledgehammer</td>
<td>5-kg sledgehammer</td>
</tr>
<tr>
<td>No. of shot points</td>
<td>375</td>
<td>268</td>
</tr>
<tr>
<td>Shot spacing</td>
<td>1–2 m</td>
<td>1 m</td>
</tr>
<tr>
<td>Geodetic surveying</td>
<td>DGPS</td>
<td>DGPS</td>
</tr>
<tr>
<td>No. of receivers</td>
<td>405</td>
<td>275</td>
</tr>
<tr>
<td>Receiver spacing</td>
<td>1–2 m</td>
<td>1 m</td>
</tr>
<tr>
<td>Maximum offset</td>
<td>~535 m</td>
<td>~282 m</td>
</tr>
<tr>
<td>Geophone</td>
<td>10 Hz, Spike</td>
<td>10 Hz, Spike</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>1 ms</td>
<td>1 ms</td>
</tr>
<tr>
<td>Record length</td>
<td>10 s (3 s used for processing)</td>
<td>10 s (3 s used for processing)</td>
</tr>
<tr>
<td>Wireless data harvesting</td>
<td>GPS time</td>
<td>GPS time</td>
</tr>
<tr>
<td>Total no. of traces</td>
<td>371,664</td>
<td>609,700</td>
</tr>
</tbody>
</table>

**FIGURE 2** An example of a raw shot gather from (a) P1 and (b) P2, showing the quality of the data and some events identified in the gathers. Note that the surface waves show much slower velocities than even the airwaves, which is a good indication of extremely slow shear-wave velocity in the medium.

P-wave velocities in the range of 1000–1500 m/s. In addition, coherent surface waves can be recognized at velocities on the order of 80 m/s, whereas the first and refracted S-wave arrivals show apparent velocities on the order of at 125 m/s and 225 m/s, respectively. They both indicate near-surface materials of extremely low $V_S$. In Figure 2b, similar observations can be made on the example shot gather from P2, although the high level of ambient noise and energetic dominance of surface waves at low frequencies hinder the identification of clear reflective events.

For both profiles, a dedicated processing workflow was designed for $V_P$ and $V_S$ estimations using the P-wave first breaks and surface-wave dispersion curves, and for reflection imaging.

**FIRST-BREAK AND DISPERSION-CURVE PICKING**

For P1, a total of 59,670 first breaks were picked and shown in Figure 3a at their corresponding shot locations,
where we highlight, in black, a sample of the picked traveltimes for better inspection. The 50,941 first breaks picked from P2 are plotted in Figure 3b. To extract the surface-wave dispersion curves, we used the automatic algorithm developed by Papadopoulou et al. (2021), which applies a moving spatial window on the data and, at each window position, picks a local dispersion curve as the maxima of the dispersion image computed according to Park et al. (1998). The code uses automatic data-driven quality control to clean each of the picked curves from noisy data points.

For the two profiles, the spatial windowing parameters were chosen after testing different window lengths and assessing the effect on the data quality. A length of 18 traces with an overlap of 3 traces (corresponding, respectively, to a distance between 18–36 m and...
3–6 m, depending on the receiver spacing) were judged as a good trade-off between spectral and lateral resolutions and were applied for the surface-wave extraction. Figure 3c shows, as example, a dispersion image (frequency–velocity spectrum) computed along P1. The dispersion curves, picked as the spectral maxima, are shown as dots. In total, 156 dispersion curves were picked along P1 and are plotted in the phase velocity and frequency domain as blue dots in Figure 3d. The solid line in Figure 3d is the average phase velocity calculated from all the curves and highlighted for better inspection of the observed velocity trends. The 123 dispersion curves picked for P2 are shown in Figure 3d in red, and in Figure 3e, the dispersion curves are plotted as a function of phase velocity and wavelength, which can be used as a proxy for the investigation depth. We observe that due to the extremely low phase velocities (60–200 m/s), indicating materials of low VS, the surface-wave wavelengths, and therefore the achievable investigation depths, are relatively short (mostly shallower than 20 m). Moreover, although the two sets of curves present similar velocities, the ones from P2 are slightly higher, indicating materials of slightly higher VS along this profile.

NEAR-SURFACE VELOCITY MODELS AND VP/V_S

For the VP estimation, we inverted the first breaks with the traveltime tomography method described in Tryggvason et al. (2002), which is a ray-tracing-based technique that uses finite-difference (FD) forward modelling (Podvin & Lecomte, 1991) and a least-square conjugate gradient solver (Paige & Saunders, 1982) to update the velocity model. To design the initial model for P1 and P2, the cell dimensions were set as 1 m in both horizontal and depth directions, chosen as the best compromise between resolution and computational time. Based on the trends of the first breaks, the initial-model velocities were set between 600 m/s and 5500 m/s, gradually increasing with depth, and a VP of 330 m/s (air) was fixed for the cells above the topography to make sure that all rays would travel downwards.

To estimate VS, the dispersion curves were inverted with the laterally constrained inversion (LCI) developed by Socco et al. (2009). It is a least-square inversion algorithm, which estimates simultaneously a 1D-layered VS model from each of the dispersion curves, using the forward Haskell and Thomson (Haskell, 1953; Thomson, 1950) solver. The model layers are characterized by their thickness, VS, VP (or equivalently Poisson’s ratio) and density, but, as surface waves are mostly sensitive to VS, the inversion is performed only for the layer thickness and VS, while the density and Poisson’s ratio are kept constant. In our case, the initial model was set assuming 156 (for P1) and 123 (for P2) 1D (layered) VS profiles located at each dispersion-curve position, that is at the midpoints of the spatial windows used for the extraction of the curves. To parametrize the models, the initial VS was set, based on the range of the phase velocities of the surface waves, increasing with depth between 60 m/s and 220 m/s for all the 1D profiles, and the layer thickness was set to 2 m for the first three layers and 3 m for the remaining two. Following Rankka et al. (2004), the initial density of the sediments was set to 1800 kg/m^3 and was increased to 2700 kg/m^3 for the bedrock layer.

For the initial VP, the corresponding velocities estimated from the first-break tomography results were used for each of the profiles.

The LCI code permits the application of regularization in the form of constraints to the allowable variation of model parameters between neighbouring models and/or layers during the model update. To choose the constraints, a series of test inversion runs were made for both profiles using different values of constraints, and each time monitoring the effect on the final misfit. It was found that a lateral VS constraint of 30 m/s with no vertical velocity constraints was the strongest constraint which did not produce an increase in the final misfit and was applied during the inversion.

The results for P1 are shown in Figure 4. The VP model obtained after six iterations of the first-break tomography is shown in Figure 4a and corresponds to an RMS misfit of 3.1 ms (chi-squared value $\chi^2(6, 405) = 23.3, p < 0.01$). Overall, VP shows increasing trends with depth, indicating sediments with VP between 1200 and 1500 m/s. Bedrock, underlying the sediments, is found at a depth of approximately 10 m in the NW and reaching 25–30 m in the SE. We interpret these velocities as clay, locally saturated, whereas the slightly higher velocities observed below the depth of 10 m in the SE (around 2000 ms, dashed line in Figure 4a) are interpreted as the groundwater table level. The VS model, which resulted after 21 iterations of the LCI, is shown in Figure 4b (horizontally interpolated for better visualization). It shows that materials with extremely low velocities (60–150 m/s) extend almost along the entire profile. The slightly higher velocities (approximately 200 m/s), which emerge near the surface in the central portion of the model (dashed circle in Figure 4b), refer to shallower than bedrock, as mapped in the VP model (Figure 4a), and probably indicate higher compaction.

Figure 4c shows the VP/VS estimated for P1. Within the investigation depth (first 10 m, determined by the investigation depth of the VS model), the estimated VP/VS values vary between 10 and 30, suggesting the high degree of saturation. In the central portion (dashed circle in Figure 4c), VP/VS becomes slightly lower (4.5–5.0), reflecting the higher velocities seen in the VS model.

Figure 5a shows the VP model obtained along P2 after four iterations of the tomographic inversion, corresponding to an RMS misfit of 3.7 ms ($\chi^2(5, 274) = 122, p < 0.01$). The velocities estimated for this
FIGURE 4  Near-surface velocity models and $V_P/V_S$ along P1. (a) $V_P$ model derived from first-break traveltime tomography, (b) $V_S$ derived from surface-wave laterally constrained inversion (LCI) and (c) $V_P/V_S$ obtained using the $V_P$ and $V_S$ models. Note the extreme high $V_P/V_S$ indicating high water content along the profile except at the windmill location.

FIGURE 5  Near-surface velocity models and $V_P/V_S$ along P2: (a) $V_P$, (b) $V_S$ and (c) $V_P/V_S$ models. Note the steep velocity gradient observed on the southeast of the profile where a sudden topography change dictated the ending position of the line towards the river.
TABLE 2  Key P- and S-wavefield reflection data processing steps applied to both profiles.

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Read SEGd data</td>
</tr>
<tr>
<td>2</td>
<td>Vertical shot stacking: 3 repeated shot records</td>
</tr>
<tr>
<td>3</td>
<td>Geometry setup: CMP spacing 1 m</td>
</tr>
<tr>
<td>4</td>
<td>First break picking</td>
</tr>
<tr>
<td>5</td>
<td>Trace editing: Noisy and dead traces</td>
</tr>
<tr>
<td>6</td>
<td>Elevation statics: 31 m, replacement velocity of 1500/100 m/s</td>
</tr>
<tr>
<td>7</td>
<td>Brute stacks</td>
</tr>
<tr>
<td>8</td>
<td>Band-pass filter: 20–40–140–180 Hz</td>
</tr>
<tr>
<td>9</td>
<td>Spectral balancing: 30–50–110–130 Hz</td>
</tr>
<tr>
<td>10</td>
<td>AGC (200 ms)</td>
</tr>
<tr>
<td>11</td>
<td>Surface-consistent residual static corrections lopped with NMO: 2 iterations</td>
</tr>
<tr>
<td>12</td>
<td>Velocity analysis: CVS, Iterative</td>
</tr>
<tr>
<td>13</td>
<td>NMO corrections: 1600/90–105 m/s, 50%/30%/stretch mute</td>
</tr>
<tr>
<td>14</td>
<td>Stack: Normal</td>
</tr>
<tr>
<td>15</td>
<td>FX-deconvolution</td>
</tr>
<tr>
<td>16</td>
<td>Balance amplitude</td>
</tr>
<tr>
<td>17</td>
<td>Migration: Finite-difference (using smoother NMO velocity model)</td>
</tr>
<tr>
<td>18</td>
<td>Time-to-depth conversion (using smoother NMO velocity model)</td>
</tr>
<tr>
<td>19</td>
<td>Export for plotting and 3D visualization</td>
</tr>
</tbody>
</table>

Abbreviation: CMP, common midpoint; CVS, constant velocity stack; NMO, normal moveouts.

used in both cases. After the inspection of the frequency spectra, band-pass filtering (20–40–140–180 Hz) and spectral balancing (30–50–110–130 Hz) were applied to attenuate the surface-wave arrivals at lower frequencies and enhance the data quality within the frequency bands where coherent reflection energy was detected. Surface-consistent residual statics (ranging between −6 ms and 10 ms for the P-wave sections and −6 ms and 6 ms for the S-wave sections), computed after normal moveouts (NMO) corrections and stacking, were applied to correct for remaining short-wavelength distortions in the data and improved the coherency of the observed reflections.

In Figure 6a, we show the same shot gather shown in Figure 2a but after some of the applied processing steps (excluding the elevation statics for comparison purposes). We observe that the strong surface-wave arrivals were attenuated, and the P- and, mainly, the S-wave reflections were enhanced, as can be better visualized in Figure 6c, where we present a zoom of the seismic data within the window shown in Figure 6a. Within this portion, a coherent event R1, probably corresponding to an S-wave bedrock reflection, is indicated by the black arrow. Additional features, indicated by the grey arrows, are likely S-wave reflections from the same origin (e.g., undulating bedrock). Improvement can be observed also for the gather from P2 (Figure 2b) for which, after processing (Figure 6b), the events which are most likely the P- and S-wave reflections from bedrock are enhanced.

To obtain the P-wave stacked sections, only the first 200 ms of the data were considered, to include bedrock P-wave reflections and isolate them from the S-wave reflections, which were seen at later arrival times. The data were common midpoint (CMP) sorted using a CMP bin size of 1 m, and constant velocity stack (CVS) velocity analysis was performed to estimate the NMO velocity model. Although picking of velocities in semblance analysis is also possible and can potentially lead to higher accuracy (e.g., Pugin & Yilmaz, 2019), semblance analysis could not be effectively performed in our case due to the high noise content of the data. It was found that a laterally and vertically invariant model of 1600 m/s provided the highest quality stacked section and was chosen for NMO corrections. A stretch mute of 50% was decided after testing different values and assessing their effect on the data. Further processing included FX-deconvolution, trace balance and FD migration. The resulting P-wavefield migrated section for P1 is shown in Figure 7a.

A similar workflow was applied to retrieve the S-wavefield reflection sections. In essence, we assumed that the observed S-wavefield reflections are of pure shear nature (S-to-S). This is justified as most of the reflections have extremely slow S-wave NMO, on the order of 60–100 m/s, which is impossible for any other wave-types such as P–S or S–P. As the P-wave NMO were observed around 1000–1500 m/s, the velocity of
converted waves, which is equal to $\sqrt{V_P \cdot V_S}$, would be in the range of 300–350 m/s (e.g., Brodic et al., 2015; Iverson et al., 1989; Yilmaz, 2001) and would require a different processing approach incorporating, for example common depth conversion binning of the data. The recognition of pure shear reflections allowed instead, and similar to Pertuz and Malehmir (2023), a simple CMP binning to be used. Velocity analysis was performed and resulted in a velocity model smoothly increasing with time between 90 and 105 m/s. The model was used for NMO corrections, with a stretch mute of 30%. The resulting S-wavefield reflection section for P1, after FD migration using the same velocity model, is shown in Figure 7b, whereas the P- and S-wavefields migrated stacked sections retrieved for P2 are shown in Figure 8a,b, respectively.

RESULTS AND INTERPRETATION

The seismic sections obtained for P1 (Figure 7) and for P2 (Figure 8) present a detailed image of bedrock topography along both profiles, and the results agree with the estimated near-surface $V_P$ and $V_S$ models. Along P1, the P-wave unmigrated stacked section (Figure 7a) indicates the bedrock reflection (R1 in Figure 7a), which appears complex and highly undulating in the NE and becomes deeper and a simpler geometry towards the SE. The same reflection is seen also in the S-wave section (Figure 7b), which presents higher quality, particularly towards the NW, where an additional horizon (R2 in Figure 7b) is present above the reflection R1.

This is confirmed also by the $V_P$ model of Figure 4a (plotted again as overlap to the seismic sections in Figure 9), which shows that bedrock depth increases from 10 m in the SE to 40 m in the NW. The shallow sediments are characterized by $V_P$ values between 1200 m/s and 1500 m/s, probably indicating highly saturated clays. In agreement with the S-wave section, a 15-m thick layer with $V_P$ ranging 1800–2500 m/s appears underneath these materials in the NW. Similar observations were made at different sites along the Göta River by, for example, Malehmir, Saleem et al. (2013),...
Salas-Romero et al. (2016), Salas-Romero et al. (2019) and Pertuz and Malehmir (2023) who observed thin layers of higher velocity coarse grained materials underly- ing or interbedding the clay sediments. According to Malehmir, Bastani, et al. (2013), these layers act as conduits for the flow of fresh water, contributing to the quick-clay formation and/or landslide triggering.

Regarding the geotechnical characteristics of the clay, observation of the $V_S$ model of Figure 4b suggests extremely low velocities (60–150 m/s), becoming slightly higher at the central portion of the line, where also the bedrock depth changes dramatically. This can explain why, although $V_P/V_S$ (Figure 4c) is extremely high (>4.5) in the NW, indicating high water content and the presence of quick-clay formations; this area has not yet failed, and the foundation of the windmill is still resilient, as opposed to the lowland in the SE of P1 (Figure 1).

To further complement the seismic observations, in Figure 10, we also present the gravity and magnetic measurements surveyed at the site during the same field campaign. Gravity values (corrected to Bouguer) are shown as spherical points along P1 with a spacing of 10 m. They show that, at the central portion of P1 and at its NW- and SE-end, the gravity values suddenly increase (arrows in Figure 10), reinforcing the interpretation of a shallow bedrock in these zones as presented in the $V_P$ model. The shallow bedrock probably acts as a local support to the overlying clay sediments, providing the necessary stability to the windmill foundation.

Nevertheless, this does not exclude the risk of collapse of the existing clays as the bedrock topography is different in other directions towards the river. This can be interpreted by comparison with the total-field magnetic results, shown in Figure 10 as lines of different colours specified in the colour bar, and because the spatial distribution of the magnetic field can be indicative of the bedrock topography. In Figure 10, the magnetic values are locally maximum near P1 (>50,970 nT, circle in Figure 10), showing that the bedrock is probably shallower in this location and provides support to the windmill foundation. On the other hand, the decrease of the magnetic values towards the river on the western side (50,850–5920 nT) suggests an increase of in bedrock depth in this direction, making this region around the windmill more prone to sliding. Geotechnical investigations are, therefore, recommended to ensure the future integrity and stability of the area.

Along P2, the S-wavefield reflection seismic section (Figure 8b) is evidently superior to the corresponding P-wave section (Figure 8a). It presents a sharp reflective horizon (R1 in Figure 8b) corresponding to the bedrock, whereas deeper features can also be observed but are not relevant for quick-clay studies and will be the subject of future research. According to this result, the bedrock
dips towards the SE, where the surface elevation suddenly decreases close to the river. As confirmed by the $V_p$ model shown in Figure 5a and similar to P1, the thickness of the sediments increases in this lowland area. Compared to P1, the estimated $V_S$ (Figure 5b) is slightly higher (100–200 m/s) and estimated $V_p/V_S$ lower (5–15) (Figure 5c), but within the ranges expected for saturated clay sediments and conditions of high water content (e.g., Donohue et al., 2012; Salas-Romero et al., 2021). Considering the sudden change in the bedrock morphology and thickening of the sediments at the slope of P2, as well as the severe topography change, this region is probably at high risk of failure. The sudden change in topography may also lead to faster erosion washing the toe of the sediments containing quick clays. We consider this region of highest risk for quick-clay landslides.

Given the successful combination of the different seismic techniques to detect this hazardous zone, it is recommended to apply seismic surveys also in neighbouring areas along the Göta River, to detect additional other possible dangerous locations and define an appropriate mitigation strategy.

**DISCUSSION**

We have shown that seismic methods are valuable for the characterization of quick-clay sites and present an important advantage. The strong contrast between the $V_p$ and $V_S$ of the clays makes it possible to leverage from different components of the seismic wavefields for subsurface characterization using a single dataset.

This was possible, despite the strong cultural noise in the data, which hindered the identification of clear P-wave reflections (Figures 2 and 6). The combination of different methods proved advantageous in this case. For instance, due to the distinct separation from the P-wave arrivals in the time-offset domain, strong S-wavefield reflections were present in the gathers (e.g., R1 Figure 6) and led to higher quality seismic images that supported the final interpretation. Not only a similar bedrock topography was found in the P- and S-wavefield reflection sections, increasing the reliability of the results, but also, the inherently higher resolution of the S-wave stacked sections revealed features not seen only from P-wave
Regarding the geotechnical characteristics of the site, the velocities estimated with CVS velocity analysis and used for NMO corrections, although falling within reasonable ranges for quick-clay environments ($V_S$ between 90 and 105 m/s and $V_P$ approximately 1600 m/s), they are not useful to identify accumulations of quick clays. These NMO velocities are dip-dependent and therefore not representative of the local properties, especially considering the highly undulating nature of the bedrock at the site. On the other hand, using the first breaks, it was possible to estimate in detail the bedrock topography and the distribution of $P$-wave velocities in the sediments. In addition, the energetic dominance of surface waves in the data, although posing as coherent noise for reflection imaging, allowed the extraction of high-quality dispersion curves and a detailed $V_S$ model of the near surface. Even though the shallow surface-wave wavelengths did not permit delineation of the bedrock, surface-wave analysis permitted to identify zones of extremely low stiffness (characterized by low $V_S$) and high water level (characterized by high $V_P/V_S$) in the shallow sediments, useful for future geotechnical assessments and hazard mitigation strategies.

In our case, only the fundamental surface-wave mode was considered, but higher modes were also locally seen. Future work involving multimode surface-wave analysis can potentially improve the final result,
FIGURE 10 Total-field magnetic and Bouguer gravity (spheres) data surveyed in the area. The magnetic measurements indicate areas of shallow bedrock and show that the sediments are thin close to P1 (circle) and become thicker towards the SE. Note that the extremely low magnetic values (blue and artefact) on the high topography along P1 are due to the windmill. The gravity measurements suggest a shallow bedrock at the windmill location and at both ends of P1 (arrows), which is consistent with the seismic results.

providing a better constraint in the LCI inversion and deeper investigation (Foti et al., 2014). Further investigations can also benefit from a joint inversion scheme, using contemporarily the surface-wave dispersion curves and P-wave first arrivals to estimate both $V_S$ and $V_P$. Although a reasonable initial $V_P$ model, based on the findings of first-break tomography, was set for the LCI $V_S$ inversion, it has been shown that joint surface- and body-wave inversion can increase the accuracy and reliability of both $V_S$ and $V_P$ estimates (e.g., Gao et al., 2022; Karimpour et al., 2022). The inclusion of other types of input geophysical data, for example, the gravimetric or magnetic measurements in a joint inversion is also possible and can provide a better constraint to the final results. Future work to optimize the use of the velocity models estimated from the P-wave first breaks and surface-wave dispersion curves for NMO corrections is also recommended, to exploit further the advantages of each method and potentially enhance the reflection seismic result.

Finally, it should be pointed out that a simple seismic acquisition scheme consisting of a vertical-impact source and vertical geophones was used for this study. Taking into account the velocities at the site, the acquisition was carefully designed to properly sample the desired wave types, that is, using narrowly spaced (1–2 m) shots and receivers and long recording times (10 s). Future works on the site can benefit from more elaborated acquisition systems, for example, with a stronger source for higher S/N data or using also shear sources and/or horizontal-component geophones to study anisotropy (Pertuz & Malehmir, 2023), lower frequencies to increase surface-wave wavelengths and achieve deeper $V_S$ estimation, and narrower receiver spacing for higher resolution.

CONCLUSIONS

Seismic methods at quick-clay sites present a unique advantage. The strong contrast between the $V_P$ and $V_S$ of quick clays and their host materials can profitably be used for the retrieval of high-quality P- and S-wave reflections from seismic datasets recorded using a standard vertical-component seismic setup. In the presented case study, the reflections were used to image bedrock topography and additional features (e.g., the layer of coarse-grained materials), which can potentially contribute to the triggering of a future landslide. Additional areas of risk were identified using the $V_P$ and $V_S$ models, obtained from the P-wave first breaks and surface-wave dispersion curves, which suggest potentially risky areas of high water content, proving that seismic methods are valuable for the characterization of quick-clay sites.

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CONFLICT OF INTEREST
All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version. This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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