GEOSTRU

# Joint MASW + HVSR analysis

Why a single technique cannot determine the velocity profile, and how to interpret dispersion and spectral ratio together with Easy MASW and Easy HVSR.

## 1. The problem: one dataset, many subsoils

*Every geophysical technique suffers from non uniqueness: many different subsoil models are compatible with the same measurement. This is not a shortcoming of the instruments: it is a property of the information the measurement carries.*

To measure how much this effect really weighs, we ran a controlled experiment. We started from a **known** subsoil profile, eight layers, with a Vs30 of 325 m/s. From that profile we generated the dispersion curve a MASW survey would have measured. Then we pretended not to know the answer and worked backwards: from the data, reconstruct the ground. Two hundred times, with different initial assumptions.

One hundred and twenty-two attempts produced a profile explaining the data with an error below 3 % — a fit any operator would consider excellent. But those profiles are not variants of the same ground.

# 122 profiles · Vs30 from 300 to 679 m/s

all compatible with the same identical dispersion curve

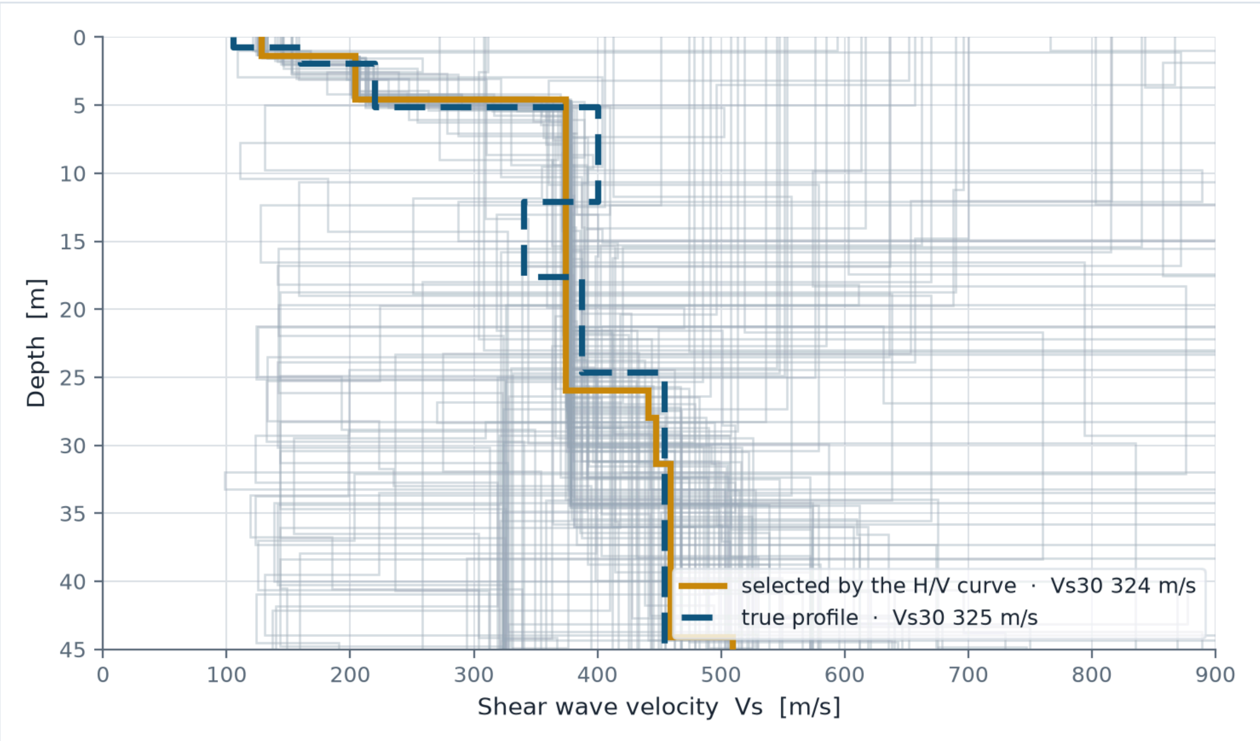


**Figure 1.** In grey, the 122 profiles that explain the same MASW dataset equally well. Dashed blue: the true profile; gold: the one selected by adding the H/V curve. Dispersion alone does not distinguish between the grey lines: it considers them all acceptable.

The boundary between **class B and class C** (360 m/s under Eurocode 8 and the Italian NTC 2018) falls in the middle of the distribution: 83 of those profiles fall in class C, 39 in class B. One profile in three, from the same data, leads to a different seismic classification.

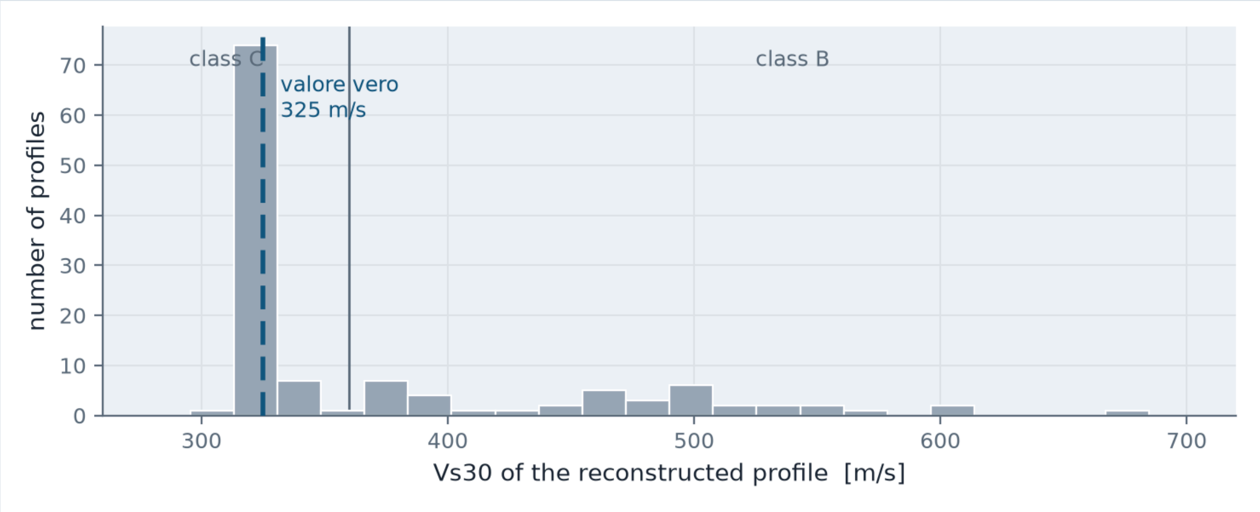


**Figure 2.** Distribution of the Vs30 values of the 122 equivalent profiles, with the subsoil class bands. The dashed line marks the true value.

> **WORTH REMEMBERING**
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> When software returns *one* profile, it is not claiming the others are wrong: it is returning one of the profiles compatible with the measurement. A low misfit says the model is compatible with the data, **not that it is the only one**.

## 2. The limits of MASW, in detail

### 2.1 The depth the data can describe

A MASW survey reliably resolves wavelengths of the order of the **spread length**. Each picked point, at frequency $f$ and phase velocity $v$, corresponds to a wavelength $\lambda = v/f$; the investigated depth lies roughly between $\lambda/3$ and $\lambda/2$.

| Spread length | Maximum useful λ | Investigated depth | Vs30 determinable? |
|---|---|---|---|
| 24 m | ~24–48 m | 8–12 m | no, largely extrapolated |
| 48 m | ~48–96 m | 16–24 m | partly |
| 72 m | ~72–144 m | 24–36 m | yes |

The comparison with the 30 m required by Vs30 is immediate. With short spreads — that is, most of those actually deployed — **the deeper part of the profile is not measured, it is extrapolated**.

> **CRITICAL POINT: POINTS BEYOND THE REACH OF THE MEASUREMENT**
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> In a real case with a 24 m spread, two points had been picked at 4.7 and 5.0 Hz with velocities of 491 and 428 m/s: wavelengths of **104 and 85 metres**, more than four times the spread length. To explain them, the inversion placed a 717 m/s substratum at 18 metres depth — a bedrock that does not exist. The fit remained excellent and no indicator flagged the problem. Once those two points were removed, the conflict disappeared.

### 2.2 Modal ambiguity

The dispersion curve is not a single curve: there is a fundamental mode and a series of higher modes. In the velocity spectrum one identifies a well defined curve and normally interprets it as the fundamental mode. **Sometimes it is not**: when energy spreads onto the higher modes, the fundamental can be weak or entirely absent, and the most visible curve is in fact a higher mode.

In our tests, attributing to the fundamental a curve that was instead the first higher mode shifted the Vs30 from 325 to **451 m/s**: a wrong subsoil class, with a dispersion fit error below 1 %. Repeated 155 times, the error proved **systematic** — always in the same direction, never random.

### 2.3 Love waves: what they would add

One way to expose the modal error is to acquire a second wave type. **Love waves**, which require transverse horizontal geophones and a dedicated source, provide a second dispersion curve that the same model must explain: a wrong modal assignment on the Rayleigh component emerges as an inconsistency with the Love component.

It should be said honestly that, in our verifications, joint analysis with the H/V curve alone proved able to reject the erroneous models in almost all the cases examined. The additional value of Love waves remains plausible and is documented in the literature, but it has **not been quantitatively demonstrated** on our data: for this reason we treat it as a possible development and not as a requirement.

## 3. What HVSR adds

The HVSR technique derives, from ambient seismic noise recorded with a three-component tromometer at a single station, the spectral ratio between the horizontal and the vertical components. The peak of that curve identifies the **fundamental resonance frequency** of the site.

### 3.1 Ellipticity: the bridge between data and stratigraphy

To derive a profile from the H/V curve, a physical model is needed that states which H/V a given ground would produce. The assumption adopted — the same used by the main scientific tools in the field — is that ambient noise is dominated by Rayleigh waves in the fundamental mode, and that the measured H/V curve can therefore be approximated by the **ellipticity** curve of Rayleigh waves: the ratio between the horizontal and vertical components of the elliptical motion a particle describes as the wave passes.

Ellipticity constrains the resonance frequency well, which to a first approximation depends on the *ratio* between the average velocity and the depth of the main contrast — not on the two terms taken separately. A slow, shallow ground and a faster, deeper one produce the same $f_0$ and almost indistinguishable H/V curves.

> **IN ONE SENTENCE**
>
> The H/V curve tells you **where the bottom is**; MASW dispersion tells you **what lies above it**. Neither of them, on its own, tells you both.

### 3.2 Why they work together

Requiring a **single** layered model to explain both the dispersion curve and the H/V curve removes most of the ambiguity: dispersion fixes the velocities of the first metres, the H/V anchors the depth of the main contrast and constrains the deeper portion the spread cannot reach. In the experiment of Figure 1, among the 122 profiles indistinguishable on dispersion alone, the one that best explains the H/V curve as well has **Vs30 = 324 m/s** against the true 325.

## 4. How the analysis is carried out

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### In the field

At the same point: the usual MASW spread with an active source, and a 15–20 minute HVSR recording with a three-component tromometer, preferably at the centre of the spread. **The two surveys must refer to the same point**: if they belong to different positions, joint analysis is meaningless.

**2** 

### In Easy MASW — picking and export

The traces are processed and the dispersion curve is picked, assigning its own mode number to each curve. Before exporting it is worth checking the wavelength of the low-frequency points ($\lambda = v/f$) and excluding those exceeding twice the spread length.

The **Export dispersion** command produces a `.dsp` file: plain text, one line per point, with wave type, mode number, frequency and phase velocity. All picked modal curves are exported.

### 3 In Easy HVSR — import and inversion

Once the H/V curve has been processed, the **Import MASW dispersion** command loads the `.dsp` file and reports the number of points and modes. The **Use MASW dispersion** checkbox enables and disables the dispersion contribution without reimporting anything: it is how you compare, on the same project, the result with and without.

The layered model is defined and **Search** is started: the inversion evaluates each candidate model against both curves, minimising the weighted sum of the two residuals.

## 5. Practical advice for the inversion in Easy HVSR

### 5.1 Building the model

- **Five or six layers**, not three. With few free parameters the model lacks the means to satisfy two curves at once, and the result is a compromise that fails both.
- **Wide search limits at depth.** The phase velocity of Rayleigh waves cannot greatly exceed the Vs of the half-space: if the data contain velocities of 400–500 m/s, a *Vs max* limit of 900 m/s on the last layer is already restrictive. Values of 1500–2000 m/s let the inversion work.
- **Total depth of at least 30 m** if Vs30 matters: otherwise that value largely depends on the half-space.

### 5.2 Whether to lock the first layer

When inverting the H/V curve alone, locking the first layer with known values is recommended, because without external information the problem remains undetermined. **With the dispersion imported, that recommendation no longer applies**: the first metres are precisely what MASW measures best. Locking the first layer to a trial value means imposing on the model information less reliable than that contained in the data.

Locking remains appropriate when the value comes from a direct measurement — a borehole, a downhole test — and not from an estimate.

### 5.3 Reading the result

**Both** computed curves must be checked, not just one: the ellipticity overlaid on the measured H/V curve, and the dispersion curve overlaid on the imported points.

| What you observe | What it means |
|---|---|
| The computed curve does not reach the points at low frequencies | The model has no material fast enough at depth: raise *Vs max* of the last layer. If the limit is already high, check that those points lie within the useful band of the spread |

| What you observe | What it means |
|---|---|
| The computed curve runs above the points at high frequencies | The shallow velocities of the model are too high; if the first layer is locked, it is the lock preventing it from coming down |
| A parameter coincides with its own search limit | It is the constraint deciding the result, not the data: widen the range to see where the inversion would actually settle |
| One curve is reproduced well and the other clearly badly | The two measurements are in conflict: look for the cause in the data (out-of-band points, wrong mode assignment, surveys at different points) before the parameters |
| Ellipticity reaches values far higher than the measured H/V | Very sharp impedance contrast: the theoretical ellipticity diverges at resonance. Insert an intermediate layer or soften the velocity jump |

Easy HVSR automatically analyses these conditions at the end of each search and reports them in the **Suggestions** box. It is worth reading it before changing parameters by trial and error: in most cases it already points in the right direction.

### 5.4 Convergence

The number of free parameters grows quickly with the layers: six layers with free thicknesses and velocities means eleven unknowns. If the maximum-iterations warning appears, it is better to proceed in two stages — first with thicknesses locked, to determine the velocities, then releasing the geometry starting from the result obtained — rather than merely increasing the iterations.

> **THE RULE THAT MATTERS MOST**
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> It is not the quality of the fit that tells us whether a profile is correct, but **how many different profiles achieve the same fit**. Joint analysis does not improve an already good result: it reduces the number of possible answers, and that is what makes the result usable.

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The experimental data cited come from controlled tests on known models, processed with the GeoStru computation engine. The choice of synthetic data is deliberate: only by knowing the exact answer is it possible to measure the error. On real data non uniqueness is greater, not smaller.

**Easy MASW** and **Easy HVSR** — GeoStru · geostru.eu
Manuals: help.geostru.io/masw · help.geostru.io/easyhvsr