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A preliminary assessment of uncertainties attributed by analysts, array types and processing algorithms for microtremor observations, via the COSMOS Blind Trials

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SUMMARY

The blind trial studies conducted for the 2006 3rd International Symposium on the Effects of Surface Geology (Grenoble, France) and the 2015 Inter-comparison of Methods for Site **Pa**rameter and Velo**ci**ty Pro**fi**le Chara**c**terization (InterPACIFIC) Workshop (Turin, Italy) evaluated the utility of microtremor array methods for characterizing seismic site conditions. These studies used a multiplicity of arrays but left an open question as to whether (and under what) conditions might sparse (low-cost) arrays be technically sufficient for the task. Similar questions arise when designing arrays for use in mapping cover thickness or buried high-velocity layers in mineral exploration.

In this study, the Consortium of Organizations for Strong Motion Observation Systems (COSMOS) blind trials used microtremor array data from four sites with geology ranging from deep alluvial valleys to an alpine valley. Data were incrementally released to approximately a dozen analysts in four phases: (1) 2-station linear arrays; (2) sparse triangular arrays; (3) complex nested triangular or circular arrays; (4) all available geological control including drillhole data. While data from one site consisted of recordings from 3-component sensors, the other three sites consisted of data from vertical-component sensors only. The sites covered a range of noise source distributions, ranging from one site with a highly directional microtremor wave field, to others with distributed or omni-directional wave fields.

Here, we review the results based on the different processing algorithms (e.g. beam-forming, spatial autocorrelation, seismic interferometry) as applied by the analysts to the incrementally released data, and then compare the effectiveness between the differing wave-field distributions. The results of the study will aid in building an evidence-based consensus on preferred cost-effective arrays and processing methodology for future studies of earthquake hazard site-effects and cover thickness studies in mineral exploration.

Key words: microtremor, passive seismic, array, SPAC, beam-forming, site hazard, cover thickness

INTRODUCTION

Past blind trials of interpretation and modelling of microtremor (passive seismic) data include one in 2006 at the 3rd International Symposium on the Effects of Surface Geology (Grenoble, France), (Cornou et al., 2007) and the 2015 Inter-comparison of Methods for Site **Pa**rameter and Velo**ci**ty Pro**fi**le Chara**c**terization (InterPACIFIC) Workshop (Turin, Italy), (Garofalo et al., 2016). These studies used a very large number of arrays and stations and provided information on best-possible results from microtremor methods; however, they did not address the issue of what simple or sparse arrays might be practical, and in what circumstances.

This blind trial organized by the Consortium of Organizations for Strong Motion Observation Systems (COSMOS) used microtremor array data from four widely differing sites in order to consider limitations imposed by differing geologies, differing sparse array geometries, and differing interpretation methodologies.

These methods include different processing algorithms within software packages (or customized in-house computer programs) which were independently selected by the participating analysts.

This summary is limited to a discussion of results from blind interpretations by 17 analysts who attempted all sites and phases. In general, 23 analysts participated, but six did not submit their analyses for two or more phases.

METHODOLOGY

Goals of the Trials

The goal of the project was to evaluate efficiency of passive seismic (microtremor) methods using:

- 2-station SPAC sparse arrays
- Sparse arrays (3 or 4-station triangles)
- Variety of software-package or custom/in-house based algorithms

In order to achieve this, the trials were divided into four phases, with each of the four sites evaluated/re-evaluated in each of the phases:

- Phase 1 – 2-station data
- Phase 2 – sparse array (e.g. 4-station triangle)
- Phase 3 – full array data (nested triangles or circles)
- Phase 4 – re-evaluation using all borehole data provided

In this preliminary assessment, we consider only Phases 1 to 3.

Sites Investigated

The four sites chosen were associated with unpublished data. These sites are:

- Site 1: Guadalupe, San Jose, California, containing a thickness of 407 m of Quaternary sediments over bedrock, maximum inter-station distance 300 m,
- Site 2: Trois Rivieres, Quebec, containing
- 30m of soft clays over 30+ m of firm clays, maximum inter-station distance 50 m,
- Site 3: La Salle, Italy, a glacial valley in the foothills of the Alps, containing 200+ m of firm sands and gravels, maximum inter-station distance 64 m,
- Site 4: Dolphin Park, Carson, California, containing a thickness of 400+ m Quaternary sediments, maximum inter-station distance 60 m.

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Site 1 was surveyed with three-component seismometers. The remaining sites recorded vertical components only. In these blind trials none of the analysts advised they employed three-component processing of the data.

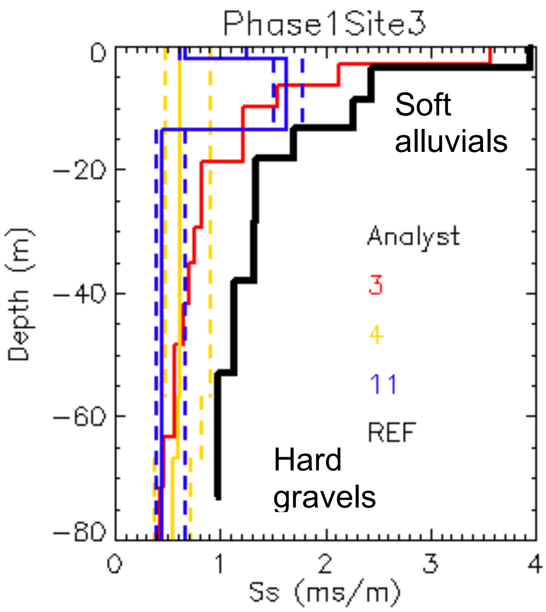

Figure 1. Site 3, Phase 1. Interpretation of layering from microtremor surface observation with a two-station array. The horizontal axis is shear-wave slowness (inverse of shear-wave velocity). Black: the reference model supplied after all phases of interpretation. Red, yellow, and blue: independent interpretations from three analysts (numbers 3, 4 and 11). Dashed lines are estimates of uncertainty by each analyst. Error estimates were not provided by Analyst 3 for Phase 1 Site 3.

Lesson from Phase 1 (Two-station Arrays)

Site 3 was an unusual site having a strongly directional source for the microtremor energy, normal to the pair of array geophones. Figure 1 shows three representative interpretations as submitted by 11 analysts. Only Analyst 11 was close in his/her attempt to address the problem posed by the directional source, thus interpretations of the velocity-depth profile were severely in error.

The same three representative analysts obtained closely matching estimates of the V_S profile when using data from two nested triangular arrays at Site 2 as supplied in Phase 2 (see Figure 2).

In contrast with Site 3, Site 1 (not shown here) had omnidirectional seismic noise, and is associated with closely matching V_S profiles, as estimated by analysts and as compared to the Site 1 reference profile.

A conclusion from the Phase 1 and Phase 2 results was that Site 3 quantifies a major risk with the two-station method when energy is directional; it is difficult or impossible to recognize the problem, and interpretations are likely to be very misleading. However, on Site 1 (with omnidirectional noise) the two-station array appeared to be challenging to analysts – only 11 of 17 analysts submitted results for this Phase 1 Site 1 test—but the results from those 11 were valid (closely matching between analyst results and reference profile).

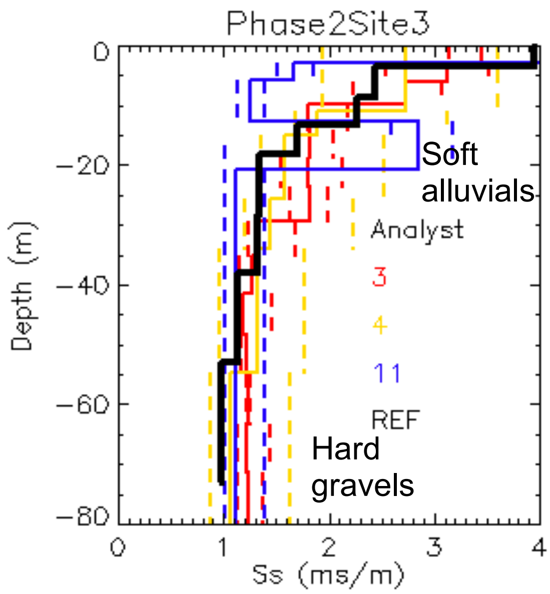

Figure 2. Site 3, phase 2. Interpretation of layering from microtremor surface observation with a nested pair of three-station triangular arrays. Colours as for Figure 1.

Frequency bandwidth achieved with different processing algorithms

Figure 3 shows a summary of bandwidths achieved in Rayleigh-wave dispersion analysis for Site 3 Phases 1, 2, and 3. As expected, the bandwidth increases as the number of geophones in the array increases (i.e. Phase 1, 2, and 3). A wide range of public-domain, commercial and in-house software packages was used by the 17 analysts but two unrelated software packages/algorithms proved most effective in terms of bandwidth achieved on this and other sites: Seisimager's Extended Spatial AutoCorrelation (ESAC) module and the Multi-Mode SPAC (MMSPAC) algorithm for direct fitting of coherency spectra (orange bands on Figure 3). Cross-correlation methods also proved very effective for obtaining high-frequency data, but less so for low-frequency data.

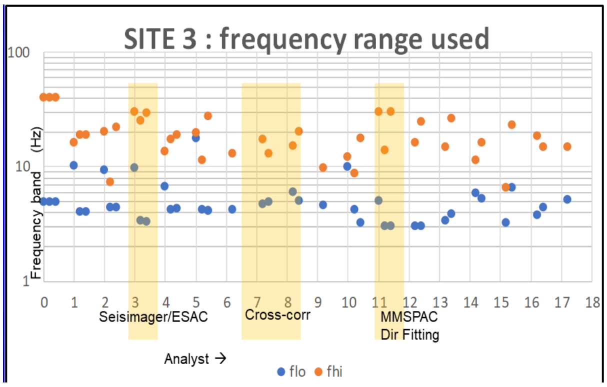

Figure 3. Site 3, Phases 1-3. Blue – minimum frequency. Orange – maximum. Horizontal axis is analyst *n* by number, with Phase 1 plotted at *n.0*, Phase 2 plotted at *n.2*, Phase 3 plotted at *n.4*. The orange bands identify software packages giving the best frequency bandwidth.

Accuracy of Interpretation by Phase

Figure 4 shows the quality of analyst results, averaged over all analysts, for each of the four sites, and each of the three phases. The quality factor or "M-value" is an empirical number (range 0 to 9) indicating the combined quality of the blind results for M_{VS10}, M_{VS30}, and M_{VS100} in terms of the fit against the site reference models, where V_{S10}, V_{S30}, and V_{S100} are estimates of the time-averaged shear-wave velocity of the upper 10, 30 and 100 meters. To calculate the fit, we use the following equation:

$$\text{Misfit} = [(V_{S30} - V_{S30\,[\text{reference}]}) / V_{S30\,[\text{reference}]}],$$

where; if Misfit ≤ 10%, M_{VSN} is assigned a value of 3; 10% < Misfit ≤ 20%, M_{VSN} is 2; 20% < Misfit ≤ 30%, M_{VSN} = 1; Misfit > 30%, M_{VSN} = 0. Here, M_{VSN} is either M_{VS10}, M_{VS30}, or M_{VS100}. Theoretically, a site yielding scores of 3 each for M_{VS10}, M_{VS30}, and M_{VS100} will result in an overall perfect score of 9. For site 1 only, the quality of fit also includes estimates of V_{S300}, thus Analyst 3 (dark blue line) and 4 (orange line) were able to achieve M-values > 9 (Figure 5). It is apparent that the gain in accuracy from Phase 2 (sparse triangular arrays on all sites) to Phase 3 (denser arrays) is small (Figure 4).

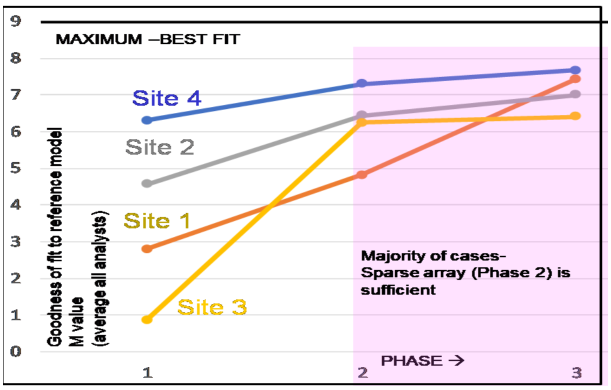

Figure 4. Quality of blind results for Phase 1, 2 and 3, averaged over all 17 analysts. Site 1: Guadalupe CA. Site 2: Quebec. Site 3: N. Italy. Site 4: Dolphin Pk, S. CA.

Accuracy of Interpretation by Analyst

Figure 5 shows the quality of analyst's results averaged over all sites, for each of the most successful ten analysts, and it also indicates the range of software packages used.

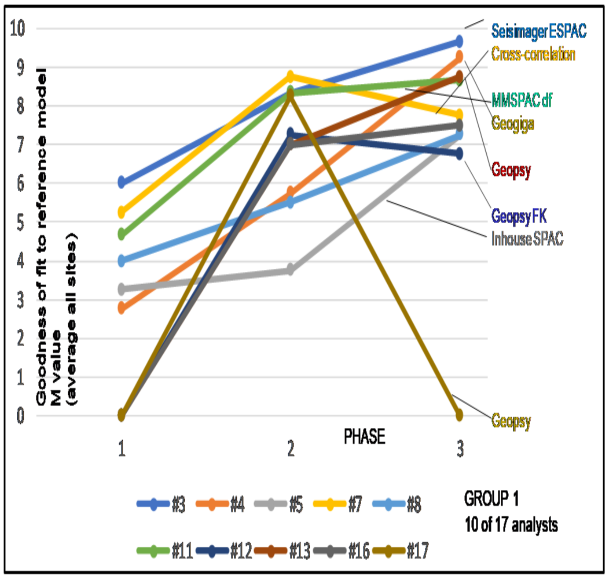

Figure 5. Quality of blind results averaged over all four sites, for the best ten (out of 17) analysts. Software packages used are annotated at right of plot.

Accuracy of Interpretation of Depth to Layer Interfaces

The quality of results discussed in Figures 4, 5 is determined by accuracy of estimates of shear-wave velocity averaged as Vs10, V_{S30} and V_{S100}. These parameters are of particular importance in earthquake hazard studies. However, it is also important in some applications, especially mineral exploration studies, to estimate actual depths to interfaces. Site 1 has a borehole PS log which provides accurate location of two important interfaces (shear-wave velocity contrasts) at depths 110 m and 407 m. This site thus provides opportunity for an assessment of the utility of microtremor methods for depth estimation of interfaces having moderate Vs contrasts.

In Figure 6 and Table 1, we show the *Vs* reference model and acceptable criterion of 40% misfit for the upper interface and 15% for the deep interface (pre-Quaternary basement). The criterion for "acceptable" was set by the scatter of actual results.

CONCLUSIONS

The two-station method does not directly address the critical factor relating to whether the energy source for microtremor wave propagation is directional. Thus, the two-station method should only be used when azimuthally-distributed sources are known to exist. For the majority of sites in this study, azimuthal distribution of sources was sufficient such that a two-station sparse array proved sufficient for reliable estimation of V_{S10}, V_{S30}, and V_{S100}.

Estimation of depth to known interfaces is a significantly greater challenge than estimation of V_{S10}, V_{S30}, and V_{S100}. Only 30% of analysts were successful in estimating depth of one of the two interfaces at Site 1, and only 15% of analysts succeeded in estimating both depths correctly.

With respect to processing algorithms, the widest usable bandwidths of Rayleigh-wave dispersion curves of microtremor data, as determined in these blind trials, was obtained with the ESAC method as implemented in the Seisimager software package and with the MMSPAC algorithm based on direct fitting of coherency spectra.

No single software/algorithm is identified as optimal. The best three analyst results in Figure 4 used three different software/algorithm packages, and five successful estimations of interface depth (Table 1) used five different software packages.

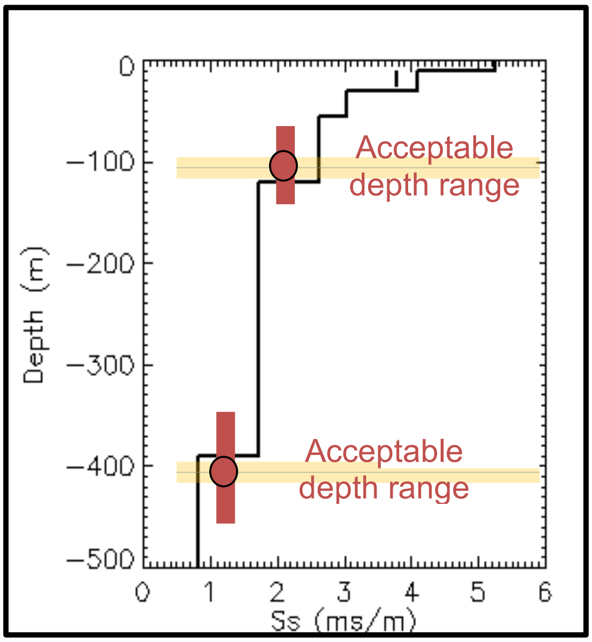

Figure 6. Reference Vs model for site 1, with empirically chosen "acceptable" depth estimate error ranges for an upper interface at 110 m, and lower interface at 407 m.

Table 1. Success rate for analysts providing depth estimates of upper and lower major interfaces for Site 1. (e.g. 6/16 indicates 16 analysts provided a depth estimate, and 6 analysts met the error criterion of Figure 6). The five analysts in Phase 3 that give correct estimates, within the acceptable ranges, for both interfaces used 5 different software packages; Seisimager, Geogiga, Geopsy, In-house SPAC, and/or MMSPAC direct fitting.

	PHASE		
	1	2	3
Interface Depth			
110 m	4/10	6/16	6/15
407 m	4/10	5/16	5/14
BOTH	**2/10**	**2/16**	**5/16**

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