

Optimisation of Surface Wave Measurements in a Solid Waste Landfill Using Geostatistical Methods

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Abstract: In solid waste landfill site characterization studies in-situ techniques are more useful and reliable because of the difficulties related to taking undisturbed samples from the site. Among these techniques spectral analysis of surface waves (SASW) takes an important place. Spectral analysis of surface waves (SASW) is a non-intrusive method for subsurface investigation that uses surface wave dispersion to indirectly determine compression and shear wave velocities. The non-intrusive nature of the method eliminates many of the health and safety concerns typically associated with conventional borings for geoenvironmental investigations. However, like any other site investigation technique, SASW profiles are generally applicable strictly only at the locations at which they are developed.

In this paper geostatistical methodology has been used to interpolate the shear wave velocity measurements taken from discrete locations in a solid waste landfill. Kriging technique was used for interpolation. This application provides a better understanding of the stiffness distribution along the site.

INTRODUCTION

Spectral analysis of surface waves (SASW) is a non-intrusive method for subsurface investigation that uses surface wave dispersion to indirectly determine compression and shear wave velocities. Advantages of SASW measurements include that they are non-intrusive, are made at known levels of stress and strain ($< 10^{-4}$ %), and involve essentially no material disturbance. SASW makes use of Rayleigh (surface) waves which propagate within a zone approximately one wavelength in depth (Stokoe et al., 1994). In ground where the stiffness changes with depth, these surface waves are dispersive in nature, which means that they travel at a velocity that is dependent upon frequency or wavelength. In SASW, analysis of the dispersion of surface waves of different frequency yields a profile of shear wave velocity versus depth. Knowledge of the shear wave velocity profile is valuable in a wide range of geotechnical problems, both directly (e.g., in a seismic response analysis) and indirectly (e.g. in evaluation of site stratigraphy). Variations of material stiffness in shear (i.e., in shear wave velocity) are often related to variations in other important properties, including density and material type (Luke and Stokoe, 1998). SASW is a particularly attractive method of investigation for landfill engineering because the non-intrusive nature of the method eliminates many of the health and safety concerns typically associated with conventional borings for geoenvironmental investigations. However, like any other site investigation technique, SASW profiles are generally applicable strictly only at the locations at which they are developed.

This paper presents a geostatistical approach to mapping (interpolating) the spatial distribution of shear wave

velocity at a given depth over the entire site from SASW measurements made at a series of discrete locations.

FIELD MEASUREMENTS

The study area (the Operating Industries, Inc., or OII, Landfill site) is located approximately 16 km east of downtown Los Angeles. The Pomona Freeway divides the 77-hectare site into two parcels: the North Parcel and the South Parcel. Landfilling operations began at the site in 1948. Over the life of the landfill, many types of waste were disposed of, including residential and commercial refuse, liquid wastes, and various hazardous wastes. In January 1984, the State of California placed the OII South Parcel on the California Hazardous Waste Priority List. The landfill stopped accepting wastes and was closed in late 1984. The U.S. Environmental Protection Agency (EPA) placed the OII South Parcel on the "Superfund" National Priority List in the same year and began conducting studies and taking actions to protect the environment, those who live near the site (approximately 23000 people live within 5 km of the site and 2100 people live within 300 m of the landfill (USEPA, 2002)), and the tens of thousands of people who commute past the site on the Pomona Freeway every day from hazards posed by the landfill. "Pre-design" geotechnical activities commencing in 1994 culminated in construction of an engineered "final cover" over the South Parcel in 1997 and 1998. These pre-design activities included a series of SASW measurements across the site. The SASW test locations in the OII site are presented in Figure 1.

In SASW testing, the ground is excited by impulse loading and ground response is measured at two or more receivers located along a common line from the energy source. Both the energy source and surface wave receivers employed in SASW testing are located on the ground surface. The depth of penetration of the surface

wave is function of the frequency and velocity, or wavelength, of the surface wave. An inversion procedure is used to determine the V_s profile of the ground from the frequency-Rayleigh wave velocity relationship deduced from the recorded ground response spectra. The frequency – Rayleigh wave velocity relationship is converted to a shear wave velocity profile based upon an assumed value of Poisson's Ratio (Kavazanjan et al, 1996, Bouazza and Kavazanjan, 2000).

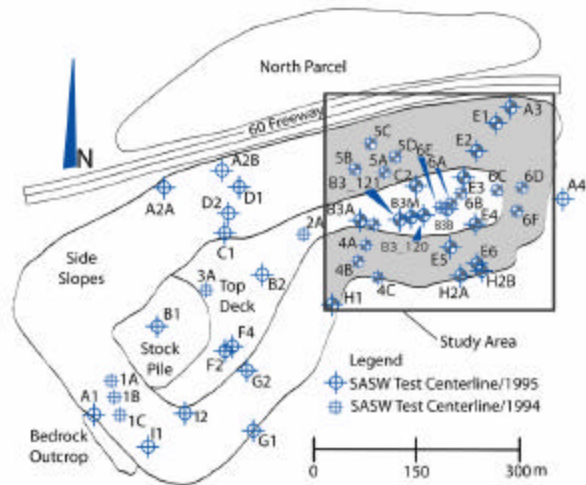


Figure 1. SASW testing locations at the OII site (GeoSyntec Consultants, 1996)

SPATIAL DATA DESCRIPTION

SASW measurements were made at a total of 41 different locations on the landfill. Twenty five (25) of these locations were underlain by at least 30 m of waste. Shear wave velocities (V_s) obtained for a depth of 9 m from these 25 points were employed to illustrate the application of geostatistics for interpolating the spatial distribution of the shear wave velocity at a depth of 9 m over the east part of the landfill as seen in Figure 3. In the work of Avsar et al, (2003), the same landfill area has been modelled using only the data from 1995 tests. However, in this paper another dataset has been combined to the 1995 data in order to improve the quality of the model. Also in the current study only the east part of the landfill has been modelled. The comparison of two different models of the same area is discussed in the final section of this paper.

In this paper the west part of the study area has been split out. The data number has been increased combining a new dataset to the 1995 data. Thus the east part of the study area could be modelled with sufficient number of data. The comparison of old and new datasets has shown that the stiffness of the material in the eastern part has a relatively smaller variability.

Table 1: Description of V_s for the study area.

Parameters	V_s (m/s)	V_s (m/s)
	1995 (Avsar et al, 2003)	1994 and 1995
Mean	179.66	166.8
Std deviation	39.37	23.03
Sample variance	1550.10	530.79
Minimum value	134.42	134.42
Maximum value	268.53	218.20
Skewness	0.90	0.42
Kurtosis	-0.08	-0.74

As seen in Table 1, after combining the 1994 and 1995 values the sample variance and standard deviation has reduced the data to smaller values. This improved the reliability of the dataset, and it provided a good base for further modelling steps.

GEOSTATISTICAL METHODOLOGY

The theory of regionalized variables (ReV) can be used to represent the distribution of natural phenomena in any given space. This theory provides an estimate of the value of the ReV at every point in the study area, both sampled and unsampled. The geostatistical methodology for assessing a ReV employs two steps to evaluate the spatial distribution and reduce the uncertainty of the ReV. The first step of the geostatistical approach is to set up a mathematical function that describes the spatial dependence of the ReV called the semivariogram function (SV) (Matheron 1963). The SV can be evaluated from the field data using equation 1 (Journel and Huijbregts 1978, Isaaks and Srivastava 1989, Sen 1998, Avsar et al. 2002):

$$g(h) = \frac{1}{2N} \sum_{i=1}^N [Z(x+h) - Z(x)]^2 \quad (1)$$

where;

$\gamma(h)$ = Semivariogram,

N = the number of pairs,

$Z(x)$ = magnitude of the ReV, and

$Z(x+h)$ = magnitude of the ReV at a point separated from the point representing $Z(x)$ by distance h .

In the second step of the geostatistical approach, once the SV function is obtained from the ReV values in the study area, kriging is applied to complete the estimation of the spatial distribution of the ReV throughout the study area. To obtain the ReV values of the unsampled points in the study area, the following equation can be used (Isaaks and Srivastava 1989).

$$Z(x_0) = \sum_{i=1}^m w_i Z(x_i) \quad (2)$$

where;

$Z(x_0)$ = the magnitude of the unsampled point,
 $Z(x_i)$ = the magnitude of sampled point i , and
 w_i = the weight coefficient for sampled point i .

Equation 2 linearly relates the magnitude of any unsampled point to the magnitude of all of the sampled points as a function of distance from the sampled points.

The values of γ_{ii} and γ_{vi} can be determined using the theoretical SV function obtained in the first step. The weight coefficients can be obtained from the following matrix by a matrix inversion procedure and after that any desired unsampled point's value can be obtained from equation 2. By applying this procedure it is possible to estimate the value of the natural phenomena at any point in the study area.

The relationship between the sampled and unsampled points is described by equation 3 (Isaaks and Srivastava 1989):

$$\begin{pmatrix} g_{11} & g_{12} & \cdot & g_{1n} & 1 \\ g_{21} & g_{22} & \cdot & g_{2n} & 1 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ g_{n1} & g_{n2} & \cdot & g_{nm} & 1 \\ 1 & 1 & \cdot & 1 & 0 \end{pmatrix} \begin{pmatrix} w_1 \\ w_2 \\ \cdot \\ w_n \\ \mu \end{pmatrix} = \begin{pmatrix} g_{v1} \\ g_{v2} \\ \cdot \\ g_{vn} \\ 1 \end{pmatrix} \quad (3)$$

where:

γ_{ii} = the value of SV between every sampled points,
 w_i = the value of weight coefficient for unsampled points,
 γ_{vi} = the value of SV between unknown point and the sampled points, and
 μ = is the Lagrange parameter.

APPLICATIONS

Experimental and theoretical SVs were developed for the shear wave velocity at a depth of 9 m in the study area (OII landfill) in order to describe the spatial dependence of V_s . As mentioned in the previous section combined dataset are used for geostatistical analysis. In order to develop a geostatistical model, first, an experimental SV is derived from the given data set and a theoretical SV is fitted to this experimental SV. A spherical model for theoretical SV was selected because the variation of the data seemed to be more logarithmic than symmetric

(Figure 2). After that, kriging technique is run to map the spatial distribution of V_s along the study area.

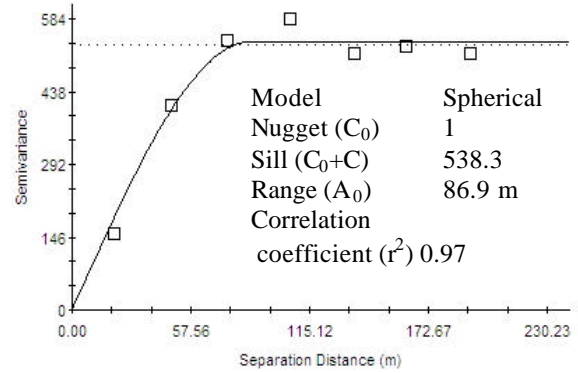


Figure 2 Semivariogram of V_s values at 9 m depth

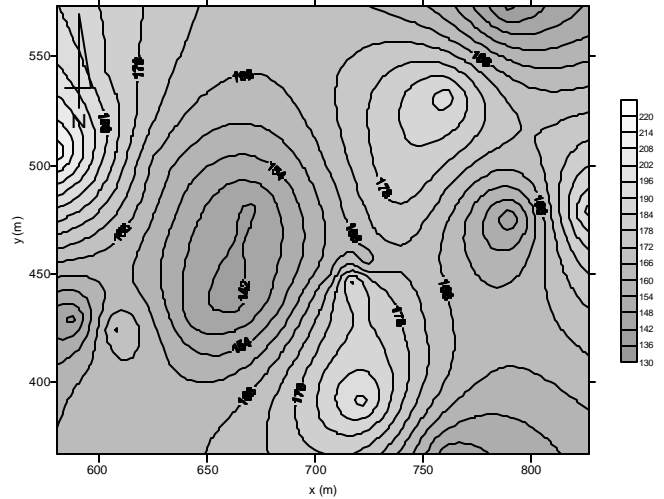


Figure 3 Kriging model of V_s values at 9 m depth

The SV models given in Figure 2 show that V_s is a highly correlated parameter because of the highly correlated theoretical SV. The variogram parameters can be seen in Figure 2. The correlation between theoretical and experimental SV is very good and this is important to make a more reliable kriging model.

The current model for 9 m depth given in this study was compared to the model published by Avsar et al (2003). As a result of this comparison it can be concluded that a better model has been achieved using the combined dataset and including eastern part of the study area. The possible reason for this improvement in the model is due to the use of a smaller study area but with denser data point distribution and decreased variation of the new dataset.

The mapping of V_s at a depth of 9 m shown in Figure 3 provides an estimation of the zones where the waste is compact and where it is less compact. The distribution of the V_s was found to vary between 130 and 220 m/s.

CONCLUSIONS

In this paper, a geostatistical methodology was used to estimate the spatial distribution of shear wave velocity (V_s) in a solid waste landfill for both sampled and unsampled points. A previous model in the same area has been improved with additional data. Geostatistical methodology has provided a better understanding of the distribution of the V_s along the study area. The same geostatistical methodology can be used for the interpolation of other in situ measurements (i.e. pressuremeter, inclinometer, etc.) or to find correlations with other parameters such as unit weight, shear strength, etc.

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