Mo 21P1 10

MASW 2D Seismic Survey in Urban Areas - The Case of the Turin Metro 1 Line

C. Alessio (AK Ingegneria Geotecnica Srl), R. Crova (Infra.To Srl), E. Duò (Tech GEA Servizi SAS) & M. Naldi* (Tech GEA Servizi SAS)

SUMMARY

The present article discuss the results of seismic investigation conducted in Turin, Italy, to assess the geological and geotechnical modeling related to the planned extension of the underground Metro Line 1 from Collegno to Cascine Vica (about 4 km of length, from Collegno to Cascine Vica). The specific objectives were to map the thickness of the man-made ground lying upon alluvial soil made of gravel and sand and evaluate the stiffness property of the subsoil. To overcome the typical obstacles of the urban ambient (electromagnetic and vibrational noise, hard traffic management, high energy source required) we applied the shallow wave technique with a continuous profiling (MASW 2D) by means of a customized system of geophones array on a land streamer and a controlled source of energy mounted on a vehicle. The surveys were performed overnight in two sessions (two days), with a fast data acquisition for a total length 2000 m. The results of the survey, calibrated with boreholes positioned all along the survey line, has precisely mapped the contact between the shallow reworked ground and the alluvial deposits. Moreover, the survey results have highlighted many lenses of cemented gravel (conglomerate bodies) inside the alluvial deposits.

Introduction

Urban areas represent some of the most challenging environments for underground civil works, and, in such a context, geophysical methods can play an important role for the assessment of the geological and geotechnical properties of the subsoil. The present article discuss the results of seismic investigation conducted in Turin, Italy, to assess the geological and geotechnical modeling related to the planned extension of the underground Metro Line 1 from Collegno to Cascine Vica (about 4 km of length, from Collegno to Cascine Vica). The specific objectives were to map the thickness of the man-made ground lying upon alluvial soil made of gravel and sand and evaluate the stiffness property of the subsoil. The surface seismic surveys were comprised of seven separate survey lines distributed along the axis of the Metro 1 Line project. To overcome the typical obstacles of the urban ambient (electromagnetic and vibrational noise, hard traffic management, high energy source required) we applied the shallow wave technique with a continuous profiling (MASW 2D) by means of a customized system of geophones array on a land streamer and a controlled source of energy mounted on a vehicle. The surveys were performed overnight in two sessions (two days), with a fast data acquisition for a total length of 2000 m. The results of the survey, calibrated with boreholes positioned all along the survey line, has precisely mapped the contact between the shallow reworked ground and the alluvial deposits. Moreover, the survey results have highlighted many lenses of cemented gravel (conglomerate bodies) inside the alluvial deposits.

Project description

The project of the extension of the Metro Line 1 westward of Turin (from Collegno to Cascine Vica) consists in the construction of a 3.7 km tunnel, single tube, double tracks, with a cross section of 65 m^2.
The bored tunnel is constructed by conventional excavation techniques. The tunnel develops all along the line in shallow condition, with a minimum overburden on the crown of less than 6m. In order to increase the tunnel stability is foreseen to implement cement grouting from the surface.
The project also includes 4 stations and 4 ventilation shafts to be constructed with cut&cover techniques between diaphragms hydromill.
From the geological point of view, Turin urban area is dominated by glacio-fluvial deposits of Rissian age (Quaternary), mainly composed by sandy gravels, cobbles and blocks, occasionally with clayey or silty sand layers. Locally, above the glacio-fluvial deposits there are silts or fine sands from aeolian sedimentation.

Three geotechnical units have been recognized along the alignment:

- UG0: Includes fill soil, consisting mainly of gravel and pebbles with little matrix. Occasionally are found fragments lateritic and asphalt scarified, the thickness unit is variable between 0.5 and 2.5 m.
- UG1: This is the main unit of the subsurface of Turin and is found systematically below the fill soil over up to a maximum depth observed of 55 m. Is made up of heterometric gravels surrounded by a sandy matrix weakly silty, color from gray to gray-brown, with lenses of cemented gravel.
- UG2: It is made by very fine sand and silt sandy , light yellow, homogeneous and moderately thickened deriving from the processes of wind erosion and redeposition. The thickness unit has a maximum of 4.5 m.

In such geotechnical context main concern related to construction are:

- depth and geotechnical properties of the fill soil, in order to define specific ground treatment schemes;
- extent and thickness of the lenses of cemented gravel that can produce difficulties during excavation related to equipment wearing and vibration.

Considering the possible geohazards listed above, the geological and geotechnical field investigation plan has included a geophysical survey with MASW2D method in most of the extension project of the

Metro line 1 and the drilling of geotechnical boreholes with DAC tests (automatic measurement of drilling parameters to evaluate the mechanical properties of soils, and namely the level of cementation, to be correlated to the soil shear resistance). Geophysical survey results has provided 2D images of the subsoil and has leaded the borehole siting according to the more problematic situation. In such a way, the investigation plan got a lot of benefits in terms of best location of the boreholes. The borehole optimization has a strong reflection also on the number of them with cost saving and impact reduction on the road traffic.

Seismic survey method

Among geophysical methods, the seismic survey is the most commonly applied for civil engineering projects. The conventional seismic surveys (refraction or reflection) can have many limitations in urban areas:

- noisy area for seismic survey (due to the road traffic vibrations);
- can take long time for data acquisition (hard traffic management);
- it requires high energy source.

For these reasons, to overcome the mentioned problems, we have applied the MASW 2D seismic method (MASW, Multiple Analysis of Surface Waves), by means of a mobile system. This survey methodology has many advantages for surveys in urban areas:

- surface waves are more energetic compared with the body waves (less energy required);
- the acquisition time is very fast, with just one shot at the end of the line and fast move of the geophone layout to the next acquisition station (slow motion without traffic interruption);
- favorable ratio between the length of the seismic line and the soil depth. MASW = 1:1 → seismic refraction = 5:1.

The basic principles of the Surface Waves Analyses is well explained in the scientific literature (e.g. Xia et al, 1999). Seismic sources generate a continuous spectrum of surface wave frequencies in a linear array of sensors (geophones). The “body waves” (primary waves, P-Waves, and secondary waves, S-Waves) have a very small amplitude compared with the shear waves (Raylegh waves), and, for this reason, sometimes are difficult to recognize. Surface waves have greater amplitude and lower frequencies compared with body waves, with a “wave train” at several frequencies. Where there is vertical velocity variation, different frequency waves travel at different phase velocities. This is called “dispersion”. By examining dispersion curves (phase velocity vs. frequency), we can determine the material properties (e.g., layer thickness, depth, Velocity of shear waves) by means of an inversion process. The interpolation of 1D MASW soundings can provide a 2D section by means of interpolating data sets .The Final 2D sections provide an “image” of the subsoil in terms of Shear velocity (Vs). Shear-wave velocity (Vs) is one of the elastic constants and closely related to Young’s modulus. Under most circumstances, Vs is a direct indicator of the ground strength (stiffness) and therefore commonly used to derive the main soil and rock properties.

MASW2D mobile system

The typical survey setup for the MASW2D profiling includes a linear sensors layout connected with a seismic cable to the seismograph (generally 24 low frequency geophones, i.e. 4.5 Hz, positioned at a small spacing, i.e. 2 m) and a source of energy positioned at the end of the line with an offset of few meters.

To improve the MASW 2D efficiency we have realized a mobile system for continuous profiling (no traffic interruption), with a controlled energy source to bypass the urban noise (Figure 1). The system is made of an energy propeller (mounted on a pickup truck) and the 4.5 Hz geophones string placed on a land streamer.

The energy propeller mass acceleration composed by: a) an impact mass (40 kg), moving on a metal guide, with an excursion motion of 40 cm; b) the traction system, made of springs pulled by a traction cable powered by an electrical engine . The energy propeller is remote controlled, and has an impact force of about 900 J (at least 3 times a heavy sledge hammer impact). This impact force is, of course,

always the same for every shot, without rebound after the impact on the ground, and provides very stable data even in heavy traffic conditions. The land streamer is a seismic cable with geophones mounted on aluminum supports positioned at regular distance (2 m) on a belt (webbing of Kevlar material). The vertical geophones have a resonant frequency of 4.5 Hz.
Data acquisition involves the following sequence of operations: a) layout of the streamer on the road and acquisition of the first point (first station point, start of the MASW2D section, conventionally at the middle of the geophones string). Because of the strong energy of the propeller, a single shot is enough to obtain good quality data, and this means time saving; b) the streamer is towed at low speed from the first acquisition point (station point 1) to the following station points, at a regular distance (in our case, 4 m). The final MASW2D section will be obtained by the interpolation of the 1-D MASW soundings positioned every 4 m of distance.
The use of a mobile system has strongly improved the seismic data quality and has dramatically reduced the acquisition time without interruption of the road traffic.

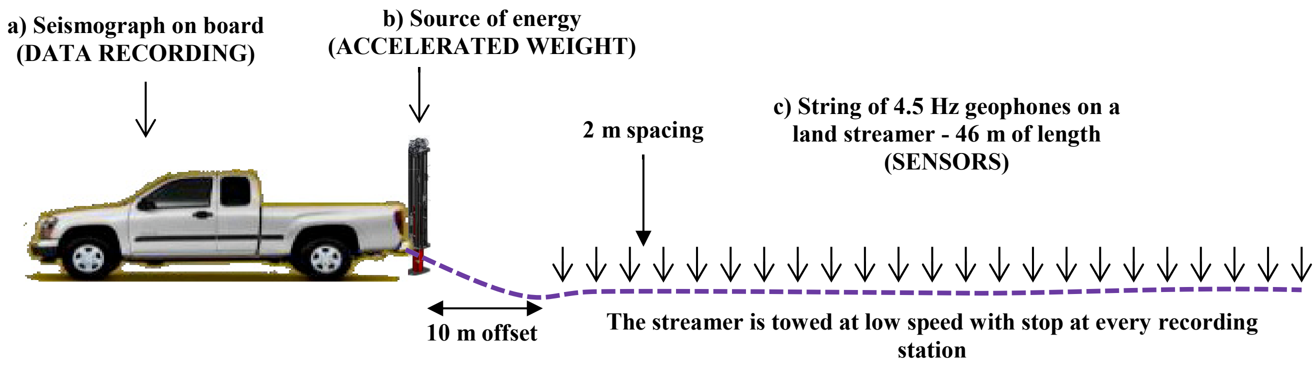

Figure 1 *Prototype of the mobile system used for the roadside MASW2D survey.*

Results

As aforementioned, the MASW2D image comes from the interpolation of adjacent 1D MASW profiles, and it has reached a typical depth of 30-35 m (largely covering the depth of excavation of the projected tunnels). Generally speaking, the geological situation provided by the MASW2D results (and calibrated with the core-log of the boreholes drillings) is quite homogeneous. The typical sedimentary sequence (shown in the MASW2D image of Figure 2) is characterized (from the ground surface) by the following materials: a) a shallow layer of reworked ground (stone and masonry rubbles in a silt/clay matrix) with a shear velocity (Vs) ranging from 100 to 200 m/s and a thickness of maximum 5-6 m (average = 2-3 m); b) a subsoil layer of natural ground made of gravel and sand with low to medium density and shear velocity of 270 to 370 m/s. This layer of natural ground corresponds to the ancient weathered soil of the glacial deposits, with a strong iron oxidation (red color of the matrix) and a low to medium density. This shallow layer can reach a depth of 8 to 10 m from the ground surface; c) underlying the natural soft ground there is cemented ground with a shear velocity from 370 to 550 m/s (weakly cemented ground) and 550 to more than 800 m/s (strongly cemented ground). According to the borehole logs, this ground is made of gravel and sand with different degree of cementation. The cementation of the ground provides a higher stiffness, which means a higher shear velocity. Thickness and distribution of this soil is irregular, but the strongly cemented ground is prevailing on the weakly cemented ground. In general, the degree of cementation (i.e. the Vs velocity) increases toward West (Cascine Vica). In addition to the geological results, for each single MASW sounding we have calculated the VS_{30} parameter for evaluating dynamic behavior of soil in seismic conditions. The results of the calculation show an increase of the Vs_{30} parameter toward West (Cascine Vica). This behavior is related to the different degree of cementation from West to East due to the deposition of calcium carbonate in the groundwater (Pleistocene age).

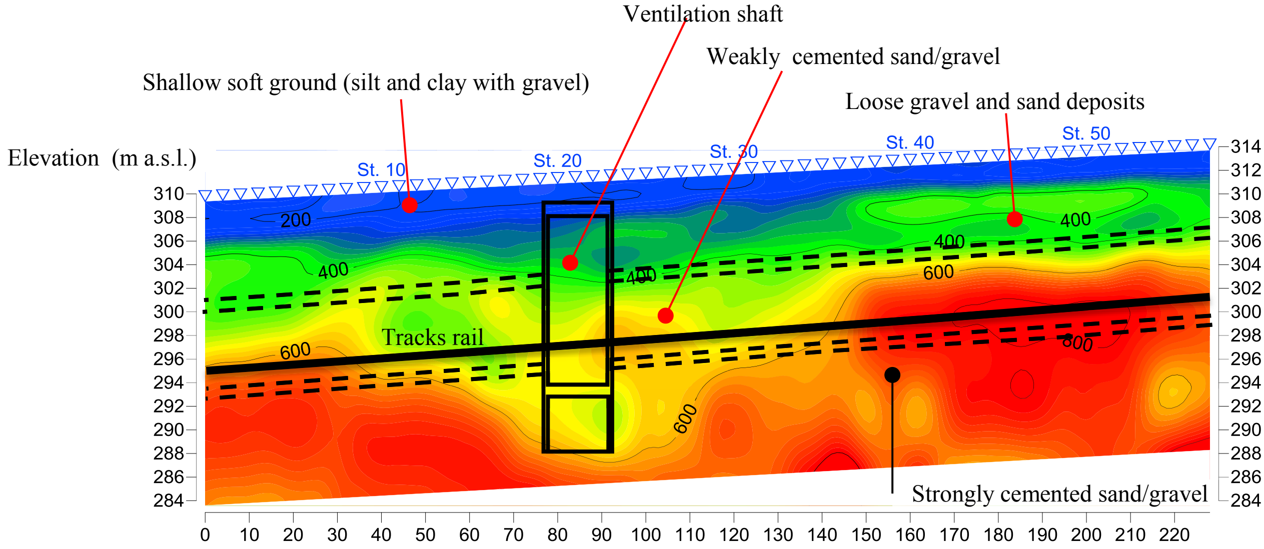

***Figure 2** Example of a typical MASW2D section. Shear velocity isolines in m/s.*

Conclusions

The geological and geotechnical characterization in urban areas for underground works can face many obvious obstacles. The use of appropriate geophysical methods, in combination with borehole drilling, can overcome most of the problems and it can provides a useful imaging of the subsoil. MASW2D with a mobile acquisition system represents one of the most efficient method for urban areas, with fast data recording and reduction of the impact on the road traffic. The case history of the MASW2D investigation survey for the Metro line 1 of Turin, presented in this article, has demonstrated the efficiency of the system in terms of cost saving, low impact on the road traffic, optimization of the borehole siting (with indirect cost saving). Moreover, the integration of geophysical and geotechnical data has provided a more realistic geotechnical model for the design of the twin tunnels.

References

Xia, J., Miller, R.D. and Park, C.B. [1999] Estimation of near-surface shear-wave velocity by inversion of Rayleigh waves. *Geophysics*, **64**(3), 691-700.