Combined geotechnical – geophysical soil investigations: a case study from Budapest

Z. Szilvágyi PhD
Geoplan Ltd., Budapest, Hungary, szilvagyi.zsolt@geoplan.hu

A.C. Kovács
Geo-Log Ltd., Budapest, Hungary, posta@geo-log.hu

J. Stickel
Elgoscar 2000 Ltd. Budapest, Hungary, iroda@elgoscar.eu

ABSTRACT: In the preliminary phase of construction projects conceptual decisions are often unsubstantiated due to the limited extent of geotechnical investigations. This results in many cases in an unexpected overflow of costs and in time delay due to unforeseen construction tasks. The extent and type of applied geotechnical investigations are often determined not only by the competition on the market, but by the lack of geotechnical experience and skill in the project management team. In this paper a case study of a typical city-center development project from Budapest, Hungary is presented, with focus on the thorough soil investigation program allowed by the elaborate project management preparation. Aim of the study is to give an overview about the state of the art of geophysical soil investigation methods applied in Hungary and to show how they can supplement and verify findings of results obtained by regular geotechnical investigations.

Keywords: geophysical investigations; seismic CPT; seismic tomography; soil investigation

1. Introduction to the development project

The development area is located in the 13th district in Budapest, Hungary, near Váci Street with a total area of 65 000 m^2. In the 1st Phase a four-storey garage basement will be built on approx. half of the area with an excavation depth of 15-17 m. Superstructures will consist of two high-rise office buildings with 60 m and 75 m height; and additionally five 30-45 m high office buildings with some smaller residential buildings between them. Exact layout of the superstructures has not been established as of the time of the ground investigations. To resolve this uncertainty, zones have been established which narrowed down the areas in which the high-rise buildings will be located.

A preliminary ground investigation program has been carried out initially in the total area to be able to compile a feasibility study for the project. This study focused on geological literature, findings in previous soil investigations in the vicinity of the development area and findings of large diameter borings, cone penetration tests and dynamic soundings. In the following chapter focus is on the subsequent detailed soil investigation program which has been carried out with the aim of providing all geotechnical information for the permit plans and construction plans.

2. Geological features

The design area is located on Pest side of the Danube river, with approx. 500 m from the shore. The currently flat area was a river meadow with shifting sand in the Pleistocene age, since earlier the shore of the Danube was located close to here. The area was affected by the migration of the Danube river channel in younger geological ages. Finally, recently shore rehabilitation resulted in filling the area. Construction works began as early as the end of the 19th century and industrial buildings, factories were built here.

From a morphology standpoint the area is a part of the Holocene age Danube River valley which is enclosed by the Pest plain from the East. The river meadow area is 500-700 m wide and its base rock layer is Miocene and Oligocene age clay, clay-marl, occasionally sandy clay which contain interbedded silty-sandy lenses. The layer is highly diverse in terms of compactness and hydraulic conductivity. According to geological maps, due to NW-SE faults, Oligocene clays, which are homogeneous and highly impermeable, are located deeper. The Miocene soils are forming here blue-green or grey, yellowish-grey clay and clay-marl layers with thinner sandy, silty interbedded layers. It must be remarked that geological classification of these ages are a controversial topic and Upper Oligocene and Miocene layers often found to be superimposed.

Over these base layers younger Danube river terrace soils were deposited, which form sandy gravel layers. The thickness varies between 5-10 m and grain size distribution is more variable compared to more eastern, older Danube terrace areas of the Pest plain, here sandy gravels, gravelly sands are typical, and they are in a loose state.

Subsequently, Pleistocene fine soils, silty sands and Holocene river meadow sediments were deposited. As the riverbank was close, organic silty and clays are also typical in these zones.

The youngest man-made fills covered the swamp areas with inhomogeneous soils with variable thickness (4-6 m).

3. Soil investigation program

The soil investigation program has been compiled based on the architectural concept which has determined which zones will contain the high rise buildings and the fact that the whole area will be built with a 4-storey garage, which requires a deep excavation support system. When designing soil investigations, construction risks must be considered. For high rise building special emphasis is laid on the conceptual design of the foundation system [1-3]. Aim of this step is to decide whether a slab foundation is sufficient (which might be the case for buildings with deep garage structures); or pile foundation is needed; or whether combined piled rafts are more cost efficient. This decision highly depends on the reliability of settlement analysis. Nowadays the state-of-the-art method for these calculations is the finite element method (FEM).

Beside the design of the foundation system, an important task is to provide geotechnical support for the modeling of the superstructure. This requires determination of spring stiffnesses and their spatial distribution in a multiple step iterative manner. The structural and geotechnical engineer must work cooperatively to achieve the compatibility of both models. Excavation support design also requires sophisticated FEM modeling considering the deep excavation level. To conclude these aspects, it should be remarked, that the cost efficient approach is to compile the investigation program with respect to these modeling tasks, so that the results of the tests allow the safe and precise definition of geotechnical parameters for the FEM modeling calculations.

Considering the project at hand 14 large diameter boring (35 – 60 m deep) and 4 CPT tests (25 m deep each) has been performed. Regular soil investigations have been supplemented with the following geophysical methods:

- two 2D surface seismic tomography sections,
- 3 downhole measurements,
- 4 borehole geophysical measurements,
- 2 seisimic CPTs,
- 4 geophysical CPTs.

CPT testing turned out to be unfeasable in some cases in the baserock layer; here additional laboratory testing for strength and stiffness paramters was performed.

4. Investigation methods

Traditional geotechnical in-situ and laboratory based investigation methods are not discussed here due to length restrictions; rather the application of geophysical methods are highlighted.

4.1. Geophysical Cone Penetration Test

The cone penetration test (CPT) has been widely used world-wide [4]; its application in Hungary is also widespread due to its cost efficiency and reliability. Geophysical CPT tests have been developed by combining CPT measurements and borehole geophysical measurments. Exploration depth depends on device details, but typically the first baserock-like layer (e.g. limestone, dolomite, sandstone etc.) is the limit; in loose sediments 20-30 m depth can be reached. It is suitable to detect layers of dissimilar properties with a thickness larger than 20 cm even in loose soils which can not be sampled with regular boring technologies. The following parameters are measured continously:

- cone resistance (q_c), shaft friction (f_s), pore pressure (u_2): the usual prime quantities measured with CPTu;
- natural gamma radiation activity (GAM): a radiation detector is located in the probe, the measurement aims to determine potassium and thorium content. Most natural soils exhibit only very rarely other radioactive materials, hence clay content will be proportional to the measured activity.
- Gamma-gamma density log (DEN): a radioactive source (Cs137) is used combined with the radiation detector to measure dispersion of Gamma rays in the surrounding layers. Measurement can provide a continous record of bulk density.
- Neutron-neutron logging (neutron porosity NPHI): a neutron source (Am-Be) is used combined with the radiation detector to measure neutron absorption in the surrounding layers. Measurement can provide a continous record of water content.

Joint evaluation of measured paramters allows the separation of geological formations (strata definition) and description of their state (qualification). Geotechnical logs are then compiled based on interpretation of geophysical borehole logging and laboratory test results if available, as well as correlations from literature. Main aim is to acquire the proportions of a four phase model for the soil:

1. radiologically inert rock matrix (usually quartz), density ρ=2.65 g/cm^3,
2. rest of the solid material: clay minerals which are gamma radiation carriers, density ρ=2.8 g/cm^3,
3. water, density ρ=1.0 g/cm^3,
4. air, density ρ=0.001 g/cm^3.

Natural gamma radiation is in proportion with clay content, neutron measurements with water content and gamma-gamma density correlates to average density of the system, hence these measurements can be used to obtain the proportions. Further correlations are used to determine shear wave velocity, v_s and compression wave velocity, v_p based on density and saturation, see e.g. [2] [6].

4.2. Borehole geophysics

Borehole geophysics include measurement methods used in boreholes used to assess the in-situ state of layers revealed in them and to describe the state of the borehole itself [7]. Measurements are performed by a probe or a series of probes lowered down into the borehole with cables attached to them for signal transmission. It must be remarked that the boring process may lead to loosening and if a drilling fluid is used, some inflow of it may also change the in-situ state. These disturbances must be assessed and addressed by correction factors.

Borehole geophysics were used in this project to measure:

- borehole diameter,
- temperature,
- natural gamma radiation,
- electric resistivity,
- micro-resistivity,
- magnetism,
- density,
- neutron porosity,
- acoustic wave propagation,
- natural-gamma energy spectra.

4.3. Surface seismic investigations

These methods were used to determine seismic shear wave velocities with tomography [8][9] and based on the same data to set up a layer model by reflection process [10]. A major aspect was to perform a set of in-situ measurements, which could provide manifold information about the top 30-50 m soil surrounding. A large scale (20 kg) S-wave hammer pendulum was used to generate shear waves on a steel plate inserted into the ground surface. Total weight of the hammer system is 120 kg. Sensors were 10 Hz natural frequency horizontal geophones pushed into the soil, or attached to a steel plate, where paving was on the surface. At each source location the hammer was used in both perpendicular directions to the measurement line four-four times. This way different polarity measurements can be used to extract longitudinal wave components from the signal by subtraction which improves evaluation.

Seismic measurements can be affected by several disturbing factors. These may be noise originating from the source or the surrounding, or other waves travelling in the vicinity of the surface (e.g. vehicle vibrations, or machine vibrations), or other absorption effects occurring during elastic wave propagation. Evaluation processes aim at compensating these factors in order to acquire a seismic signal which describe the soil stratification reliably.

Evaluation consists of [10]:

- removing noisy channels,
- subtraction of opposite polarity measurements at single point,
- frequency filtering based on spectral analysis,
- surface wave noise attenuation,
- surface consistent deconvolution,
- normal moveout correction,
- velocity analysis,
- summation.

Seismic tomography is aiming at determination of shear wave velocity profile (or in some cases energy absorption profile) based on recorded signal. The inverse problem is solved in an iterative manner with finite difference method.

4.4. Downhole measurements

The boreholes were drilled and lined with PVC case and cement and then investigated with a five-component probe developed by Geo-Log Ltd (Figure 1).

Figure 1. Geo-Log Ltd developed downhole unit without pneumatic system

The probe contains a vertical and four horizontal geophones aligned in a 45° rotation to each other. Compared to the regular three-component probe (containing a single vertical and two horizontal geophones aligned in a 90° rotation) this device allows a more precise identification of shear wave arrival. Connection to the lining is provided by a compressible rubber packer. The most crucial task proves to be the elimination of different tube waves, which can be achieved by removal of water from the borehole. In the case of water filled boreholes the development of large amplitude tube waves in the tube-water-soil system cannot be avoided which makes the detection of shear wave arrivals unfeasible.

5. Results

During the assessment the benefit of having results of multiple investigation methods concerning a material parameter has been clear. The following figures show comparisons of parameters obtained with different methods.

Figure 2. shows compression- and shear wave velocity profiles measured with different in-situ methods. Agreement between methods are satisfactory and the uncertaintiy, scatter of the results can also be assessed.

Figure 3. shows the stratigraphical section obtained by the geophysical CPT test. Layer boundaries are determined based on cone resistance (red) and shaft friction (magenta) results as well as geophysical measurement results such as density (green), neutronporosity (dark blue) and natural gamma values (light blue).

Figure 4. shows a comparison between shear wave velocity values obtained with correlations form GCPT measurements and seismic tomography. A very good agreement can be observed.

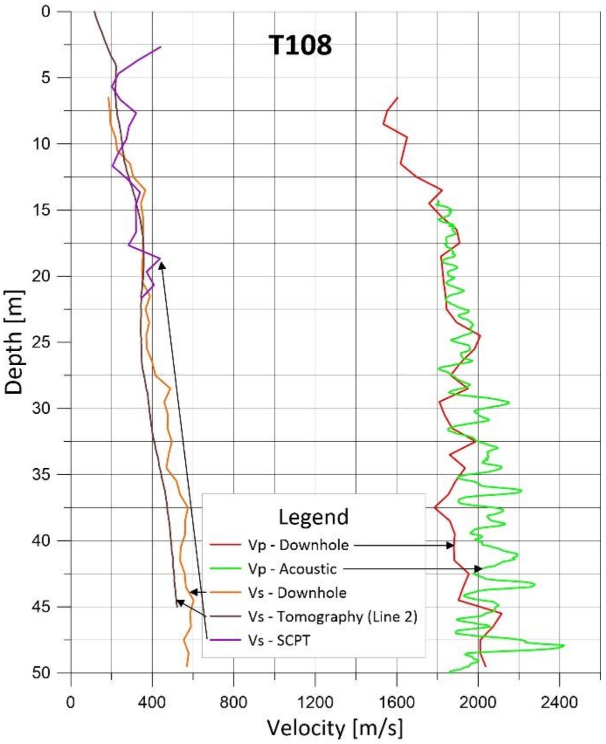

Figure 2. Shear- and compression wave velocity profiles measured with downhole (red), acoustic (green) and SCPT (magenta) measurements

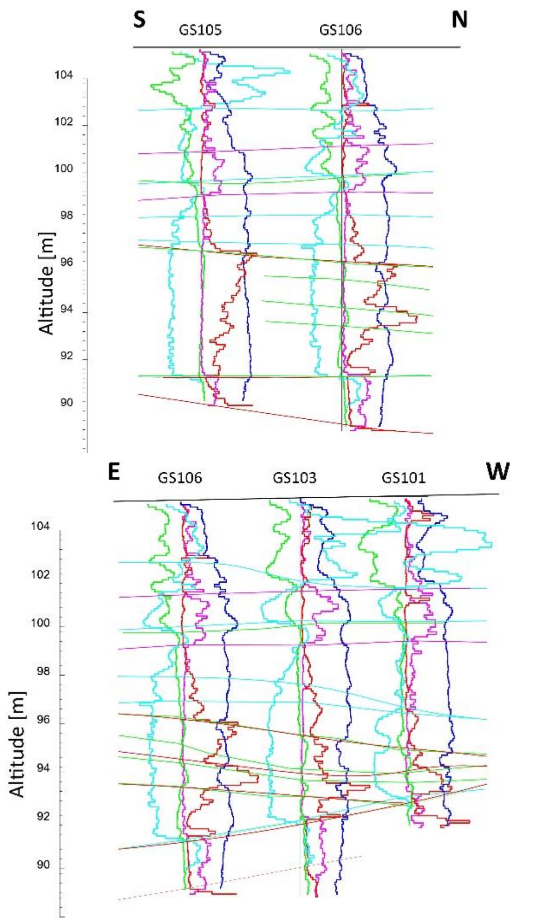

Figure 3. Stratigraphical section based on GCPT results (dark blue: neutron porosity, green: density, light blue: natural gamma, red: cone resistance, magenta: friction ratio)

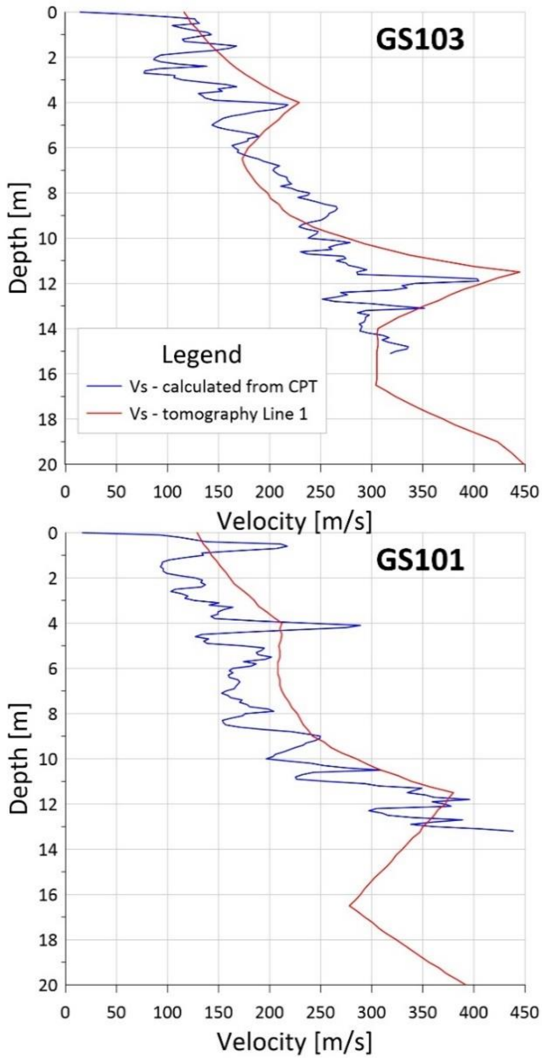

Figure 4. Shear wave velocity profiles based on GCPT measurements and seismic tomography

A typical stratigraphical section can be seen in Figure 5. Geophysical measurement results were especially beneficial in separating the Miocene baserock layer surface and in refining layer boundaries obtained from geotechnical borehole logs. Density values measured on soil samples taken into the laboratory were in good agreement with results obtained from borehole geophysics. An interesting feature of this particular site is, that neither the geotechnical investigations, nor geophysical measurements were able to distinguish separate sublayers within the Miocene layer. This is in accordance with geological literature, as in this area in this geological time deposition and sedimentation of different fractions was typical in the Miocene sea. All measurement methods have confirmed the spacial inhomogenity of this layer which resulted in a scatter of soil classification parameters as well as state variables. Without the results of the geophysical measurements it would have been a considerable challenge to assess shear strength and stiffness measurement results performed on undisturbed samples. The scatter was so large, that if one tried to assess layering based on them, unresolveable contradictions would have arisen.

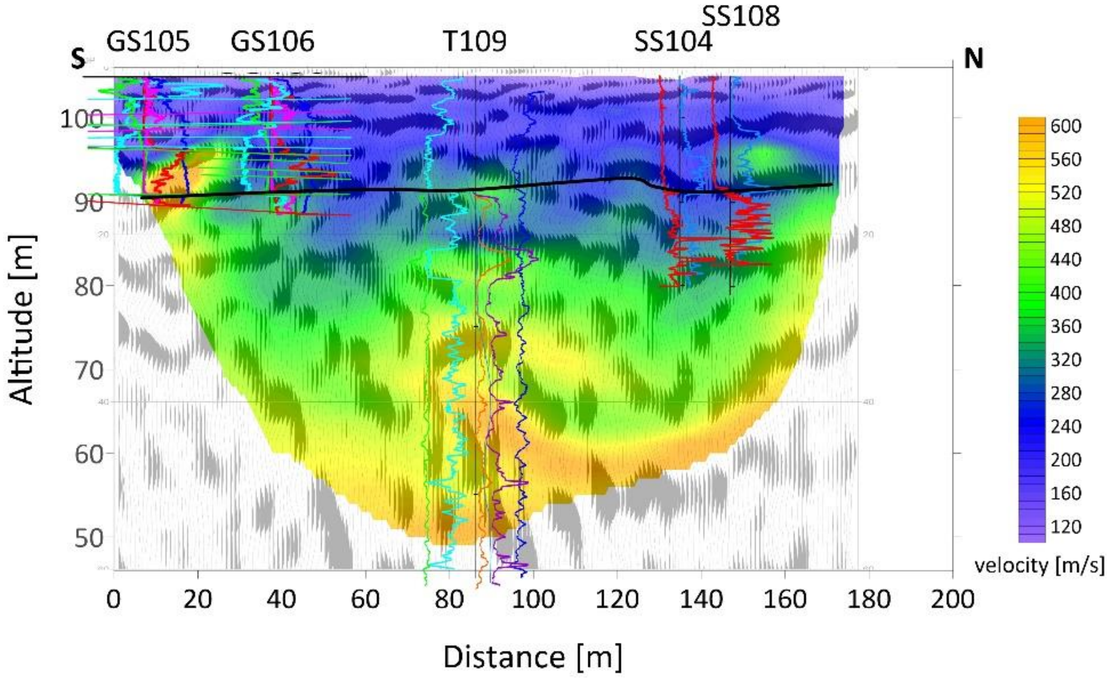

Figure 5. Stratigraphical section based on seismic reflection, tomography, GCPT, and borehole geopysics. Lines: dark blue: neutron porosity, green: density, light blue: natural gamma, red: cone resistance, magenta: friction ratio (GCPT); and micro resistance (borehole geophysics); orange: electrical resistance; black: boundary of tertiar layers

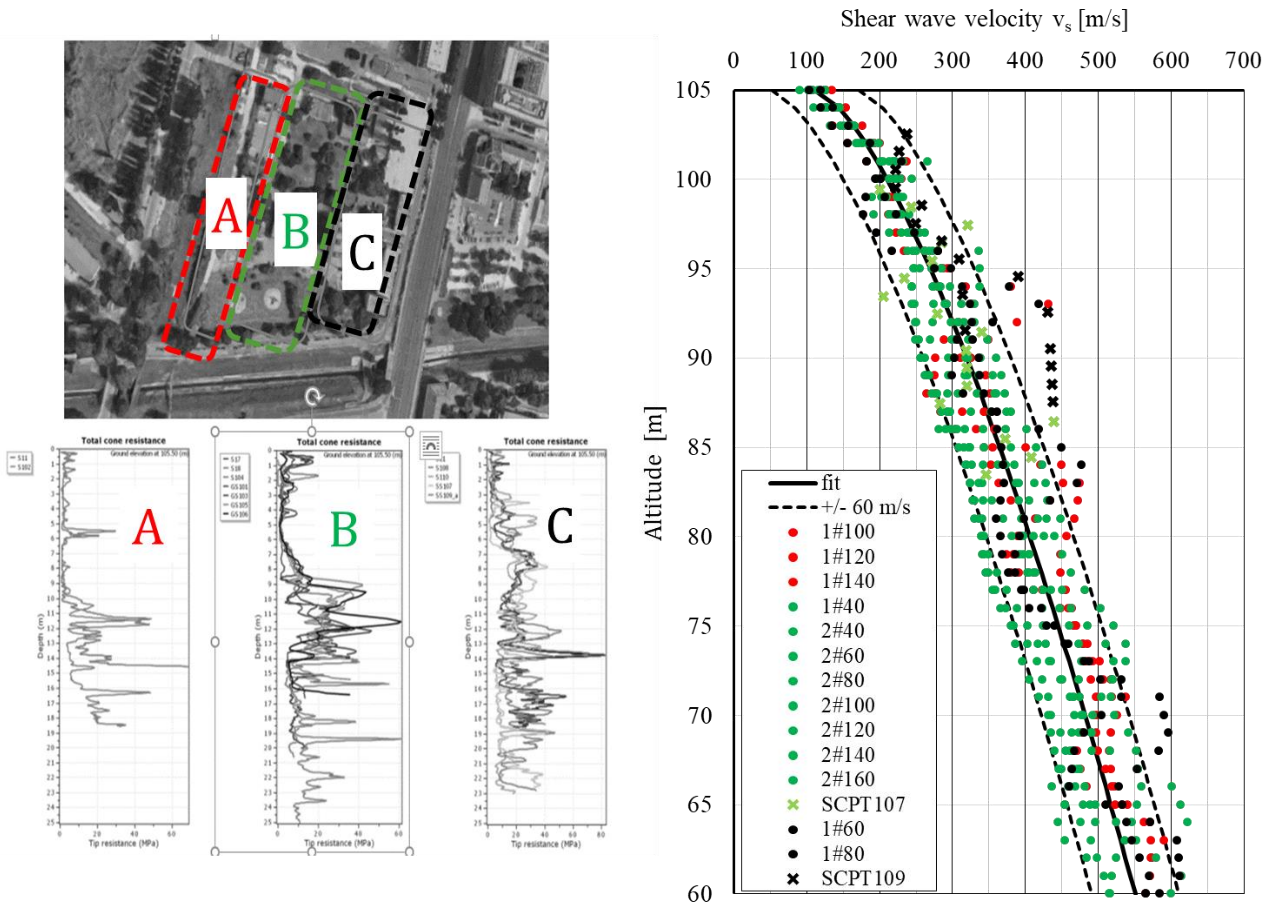

Figure 6. Shear wave velocity distribution throughout the design area (left: q_c from CPTs, right: v_s from seismic reflection, tomography, GCPT)

Shear wave velocity measurements were analyzed in order to divide the development area into zones if possible. The distribution of measured v_s values in different sections of the area is shown in Fig. 6 on the right, with typical CPT cone resistance values shown on the left. Although no subsections could be identified based on v_s, the determined scatter of measured vales throughout the whole area is a valuable information for seismic design considerations.

Another important task for such a project is the groundwater management during excavation. This can be helped by the results of borehole geophysical measurements, namely differential temperature measurements which detect seepage in the groundwater. In this case based on the measurements in the Miocene base layer, only a few seepage positions were detected, therefore sand layers do not appear continously within the baserock. This is an important finding considering dewatering of the excavation.

6. Conclusions

The presented complex investigation program and the joint assessment of geotechnical and geophysical measurements allowed a comprehensive analysis of geotechnical features of the site. Different geophysical methods complemented geotechnical investigations well and allowed a better understanding of spatial variability. This feature is difficult to assess with geotechnical methods which use only local samples.

An important parameter obtained with geophysical methods is the shear wave velocity, which is necessary for seismic design based on Eurocode 8. If v_s measurements are available, site classification according to Eurocode 8 can also be made more precisely; and even local design spectra can be developed in order to assess seismic response of designed structures more precisely and economically [11]-[14].

Many state-of-the-art material models used in numerical analysis also require this parameter to describe small strain stiffness, e.g. the Hardening Soil Small or the Ramberg-Osgood material model [14]. These models allow the more precise calculation of displacements around excavation support structures and forces in them; settlement behavior of foundation systems can be analyzed; and soil-structure interaction problems can be assessed economically, if in-situ or laboratory measurements are available for parameter determination. Geophysical measurements presented in this study can be used for this task; seismic tomography, GCPT, downhole measurements for obtaining v_s, borehole geophysics and GCPT for obtaining density. Small strain stiffness, G_0 is then calculated directly.

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