Numerical Simulation of Non-Destructive Foundation Pile Tests

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Abstract. New foundation piles are tested after construction for quality control in many European countries as well as overseas. Length and integrity have to be checked. The test of old foundations becomes more and more important in the frame of re-use in urban areas or bridge inspection.

Most of the available non-destructive methods (mainly acoustic) are in use since several decades. They work well in many situations. But the interaction with complicated geometries or soil structures is still not fully understood. Numerical simulation provides important insight into wave propagation depending on foundation and soil properties.

We use a specially adopted 2D finite integration technique for cylindrical geometries (CEFIT) for our simulations of measurements with the low strain pile integrity testing method and the parallel seismic technique. After solving problems with the modelling of the pile/soil interface we are able to investigate the influence of e.g. pile geometry variations or soil layers. The results are used to improve the interpretation of real data.

Various results are presented and compared to data from construction sites and our recently constructed validation piles.

1. Introduction

Foundations are one of the most important (and often moist expensive) parts of building structures. If they fail, the entire structure may fail. Quality control and checks before change of usage or load are difficult as the elements buried deep in the subsurface. One has to take in mind that many structures are built at sites with difficult soil conditions (e. g. high rise buildings in the financial districts of London or Frankfurt) or risk of earthquakes (California, South-East Asia).

Many non-destructive testing methods for foundations have been developed in the last decades. Several countries have developed recommendations or standards [1][2][3]. Recently a European research project has been completed dealing with possibilities for foundation re-use [4]. In the frame of this project several cases occurred where the conventional use of these techniques failed or lead to inaccurate results. The reasons have been unconventional foundation features or certain measurement parameters. Some of the effects were not fully understood. Thus a numerical simulation tool was developed to assist the research and development work in this field.

2. Testing methods

2.1 Low Strain Pile Integrity Testing (PIT)

The most used non-destructive method for existing pile foundations is the low strain pile integrity testing method (PIT). A hammer impact on the pile top generates an elastic wave, which travels down the pile and is reflected at the toe and major flaws (necks, cracks, extensions). A sensor on the pile top measures the travel times (figure 1). The depth of toe or flaws can be calculated by

$$d = \frac{t_r}{2v_p}, d = depth, t_r = traveltime, v_p = wave\,velocity, \qquad (1)$$

The PIT method is part of many standards and regulations [1][2][3] and is well accepted. Main problem is the need of calibration (wave velocity), resulting in accuracy for pile length determination of 3-10%. The results are influenced by pile type, soil, casing and other parameters and are subject to interpretation.

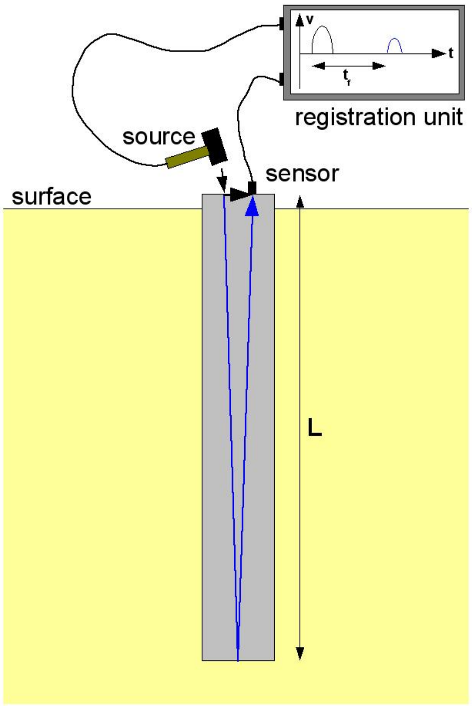

Figure 1: Principle of Low Strain Pile Integrity Testing (PIT).

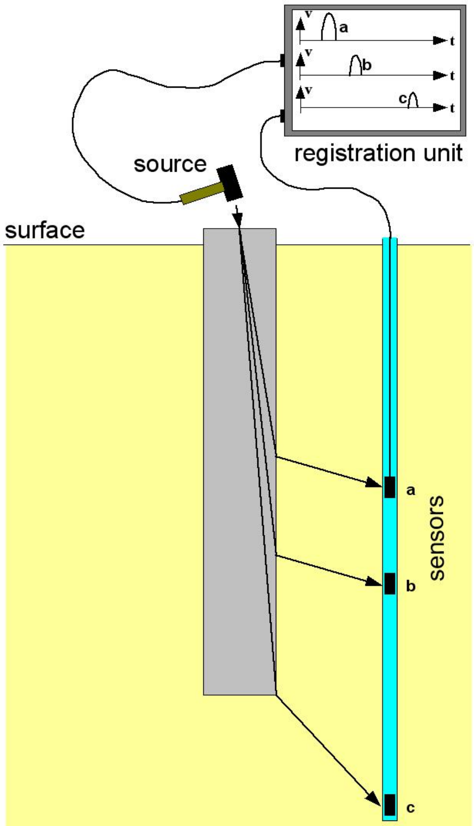

Figure 2: Principle of Parallel Seismic Testing (PS).

2.2 Parallel Seismic (PS)

The Parallel Seismic method uses the same type of impact as PIT, but the wave propagation is monitored in a nearby borehole, e.g. by a chain of hydrophones (figure 2). The first arrival time of the waves are plotted vs. depth. The slope of the curve matches in the upper part the wave velocity in the pile, in the lower part the wave velocity in the soil. The section in between marks the pile toe. By new interpretation techniques the pile length can be determined with an accuracy of up to 2 % without calibration. Due to the need of a borehole the method is slower and more expensive than the use of PIT. A proper combination of both gives optimum results in terms of cost and accuracy.

3. Simulation technique

Supposed that the mechanical impact hits the pile at the centre, the pile is rotational symmetric and the soil has only horizontal layers, the simulation problem can be simplified from 3D to 2D. We use a Finite Integration technique (CEFIT) developed by Schubert et al. [], adapted by Schubert to the pile testing problem. For data evaluation and graphical representation we use custom software or commercial products.

3.1 CEFIT

The CEFIT technique was introduced by Schubert and others and is described in much detail in [6] and [7]. The description here follows these publications.

The subsurface is divided in small cells in cylindrical coordinate system (φ,r,z), centred at the pile axis. The source impact (half sine cycle of variable width) is applied at the top centre of the pile. As the problem is axisymmetric, the 3D cells can be replaced by 2D elements in the φ=0 plane(figure 3).

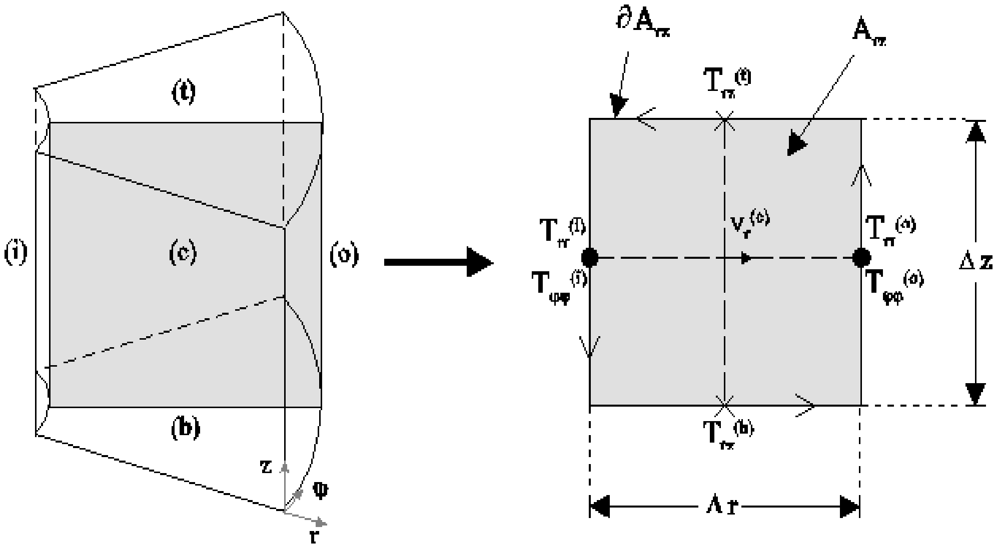

Figure 3: 3D cell and corresponding 2D element, where the differential equations are solved by integration along the border (thin arrows) [7]. Particle velocity v is given in the centre, stress components T_{ii} at the borders (“staggered grid”).

The discrete equation read [7]:

$$\rho \dot{v}_r^{(c)} = \frac{T_{rr}^{(o)} - T_{rr}^{(i)}}{\Delta r} + \frac{T_{rz}^{(t)} - T_{rz}^{(b)}}{\Delta z} + \frac{T_{rr}^{(o)} + T_{rr}^{(i)} - T_{\varphi\varphi}^{(o)} - T_{\varphi\varphi}^{(i)}}{2r^{(c)}} + f_r^{(c)} \ , \qquad (2)$$

$$\rho\dot{v}_z^{(c)} = \frac{T_{rz}^{(o)} - T_{rz}^{(i)}}{\Delta r} + \frac{T_{zz}^{(t)} - T_{zz}^{(b)}}{\Delta z} + \frac{T_{rz}^{(o)} + T_{rz}^{(i)}}{2r^{(c)}} + f_z^{(c)} \quad , \tag{3}$$

$$\dot{T}_{rr}^{(c)} = (\lambda + 2\mu)\frac{v_r^{(o)} - v_r^{(i)}}{\Delta r} + \lambda\left[\frac{v_z^{(t)} - v_z^{(b)}}{\Delta z} + \frac{v_r^{(o)} + v_r^{(i)}}{2r^{(c)}}\right] + g_{rr}^{(c)} \, , \tag{4}$$

$$\dot{T}_{\varphi\varphi}^{(c)} = (\lambda + 2\mu)\frac{v_r^{(o)} + v_r^{(i)}}{2r^{(c)}} + \lambda\left[\frac{v_r^{(o)} - v_r^{(i)}}{\Delta r} + \frac{v_z^{(t)} - v_z^{(b)}}{\Delta z}\right] + g_{\varphi\varphi}^{(c)} \quad , \tag{5}$$

$$\dot{T}_{zz}^{(c)} = (\lambda + 2\mu)\frac{v_z^{(t)} - v_z^{(b)}}{\Delta z} + \lambda\left[\frac{v_r^{(o)} - v_r^{(i)}}{\Delta r} + \frac{v_r^{(o)} + v_r^{(i)}}{2r^{(c)}}\right] + g_{zz}^{(c)} \quad , \tag{6}$$

$$\dot{T}_{rz}^{(c)} = \mu\left[\frac{v_r^{(t)} - v_r^{(b)}}{\Delta z} + \frac{v_z^{(o)} - v_z^{(i)}}{\Delta r}\right] + g_{rz}^{(c)} \quad . \tag{7}$$

where v_i and T_{ij} with i, j = r,φ,z are the components of the particle velocity vector and of the stress tensor, respectively. The f_i and g_{ij} components represent force and stress sources. The elastic properties of an isotropic solid medium are given by the two stiffness coefficients, the Lamé constants λ and μ, and the mass density ρ.

These equation have to be set up all elements leading to large linear equation systems. The particle velocity and the stress tensor are determined one is procedure has to be solved for each time step using an central difference operator [7]:

$$\begin{aligned} v_i^{(k)} &= v_i^{(k-1)} + \dot{v}_i^{(k-1/2)}\Delta t \quad , \\ T_{ij}^{(k+1/2)} &= T_{ij}^{(k-1/2)} + \dot{T}_{ij}^{(k)}\Delta t \quad , \end{aligned} \tag{8}$$

where the index (k) denotes full and (k ± 1/2) denotes half-time steps of Δt with t = k Δt. CEFIT uses a staggered grid (particle velocity and stress components are calculated at different positions.

To avoid instability and guarantee accuracy the element sizes and the time step length must fulfil certain conditions depending on the speed of the elastic waves and impact frequency:

$$\Delta t \le \frac{1}{c_{\max}\sqrt{1/(\Delta r)^2 + 1/(\Delta z)^2}} \quad , \tag{9}$$

$$\Delta r, \Delta z \le \frac{1}{10}\frac{c_{S,\min}}{f_{\max}} \quad , \tag{10}$$

See [7] for details.

3.2 Pre- and postprocessing

Generally each of the elements of the CEFIT grid can have separate material parameters. As this procedure is work intensive and the algorithm sensible to errors in the input data, a text based preprocessor was developed by Schubert [8] in cooperation with the author in the frame of the RuFUS project. It makes input of soil and pile parameters and features easy and calculates proper values for cells sizes and time steps to avoid instability and numerical dispersion. Figure 4 shows the subsurface geometries offered by the software.

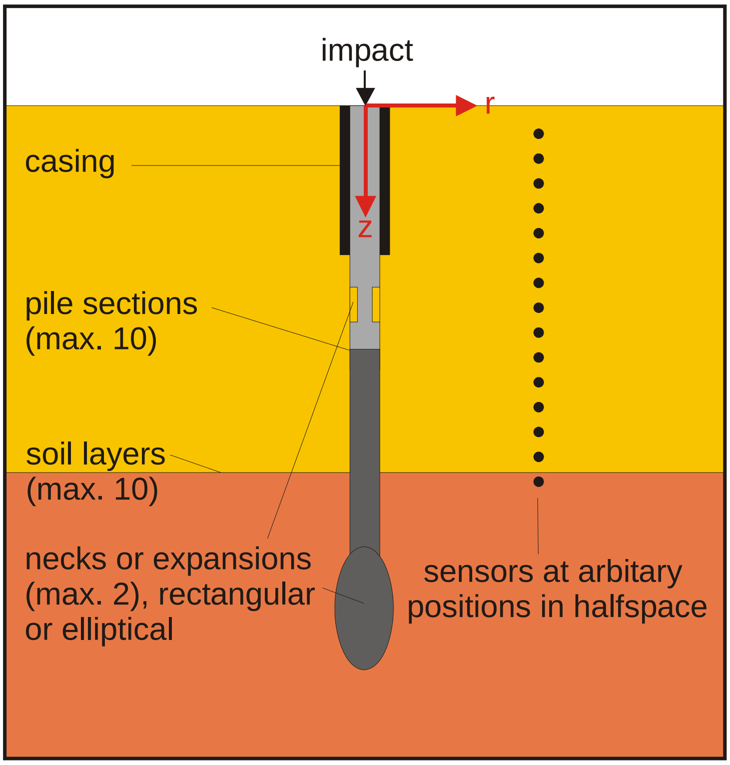

Figure 4: Subsurface geometry used in the simulation software.

In addition a module for data export to a commercial seismic software program was written. Other postprocessing software (basic filtering, graphics, snapshots, video clips) was added.

3.3 Coupling pile to soil

The numerical procedures described in section 2.1 assume a perfect coupling between pile and soil. This leads to a limited impedance contrast and dissipation a big part of the wave energy to the soil. This is not the case in reality. The coupling is often weak. To simulate this, a narrow layer (one or two elementary cells wide) has been introduced between pile and soil (side and/or bottom). The coupling layer has a high impedance contrast to the soil and pile properties (e.g. using the elastic properties of water).

3.4 Some snapshots

As a simple example the test of a 10 m cylindrical pile without any flaws in homogeneous soil was simulated Figures 5 and 6 show snapshots after 2.6 and 5.2 ms. The grey scale values correspond to the individually scaled amplitude (max. amplitude =1). The first snapshot shows mainly a down going wave in the pile and a head wave with straight wave fronts in the soil. The second snapshot was taken after reflection at the pile toe. An elastic wave goes up, other waves have been generated at the reflection event.

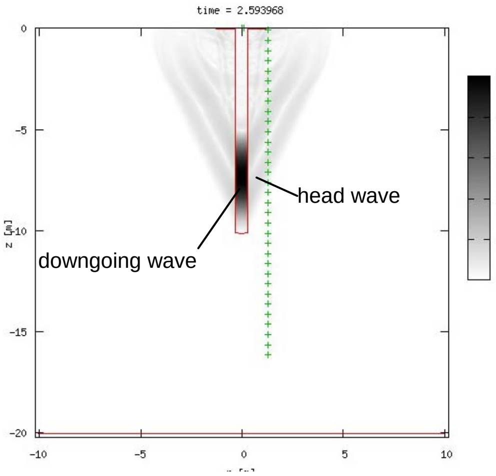

Figure 5: Snapshot at 2.6 ms

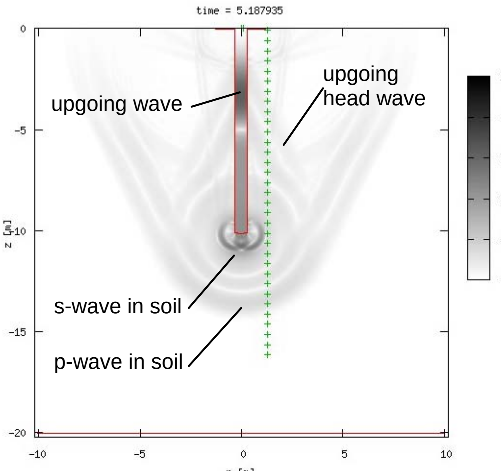

Figure 6: Snapshot at 5.2 ms

4. Application example: Improved interpretation of parallel seismics

The wave velocities in piles calculated from parallel seismic results are often higher than expected. A B25/C30 concrete should have around 3750 m/s [5]. Measurement results are often 4000 m/s or higher [9]. One possible source for apparently higher velocities may be borehole or pile inclination. A set of simulations was done to investigate this question (Figure 6).

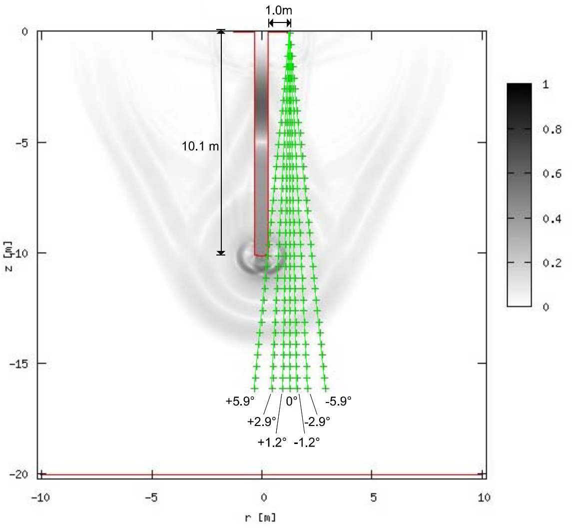

Figure 6: Snapshot of simulation results for a 1 ms hammers impact on a 10.1m pile. Greyscale: Amplitude of z-component 5.2 ms after impact. Crosses: simulated sensor positions.

Figure 7 shows the evaluation of the results. The interpretation of the simulated data was done using a technique described in [10]. The velocities are in general overestimated (as in field measurements). For zero degree inclination the value is 7% higher than reality. The pile velocity depends almost linear on borehole inclination. This means, that the use of this parameter for concrete quality estimation is limited, as pile and borehole will never be exactly parallel (inclination 0°) and inclinometer data (strongly recommended) will not available at all sites. The pile length is less influenced by inclination but underestimated in most cases, but no more than 4% for all but one case (inclination +5.9° means here a borehole touching the pile toe).

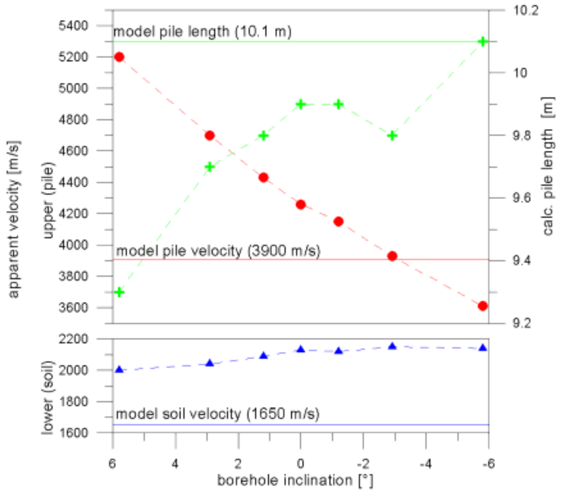

Figure 1: Evaluation of parallel seismic simulation results for different borehole inclinations.

5. Conclusions

The CEFIT simulation software has proved to be a useful tool for the optimisation of pile testing and the corresponding interpretation techniques. It can be used to check the influence of unusual pile geometries on the testing results or to validate the accuracy of interpretation algorithms.

6. Acknowledgements

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