

Geophysical Methods in Civil Engineering: Overview and New Concepts

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Abstract

Geophysical methods have been used in civil engineering for decades. The main field of application is - to no surprise - in geotechnical projects from site characterization to foundation quality assurance. For more than 25 years, ground penetrating radar (GPR) and seismic methods have found applications in structural engineering. Recently introduced geophysical methods have been adopted to ultrasonic investigations in various fields. They help to improve the quality of structural imaging and to detect small changes in concrete. An overview of the history and current use of geophysics in civil engineering is given. Selected examples of new concepts include advances in wave based imaging, quality assurance for foundations, detecting small changes in concrete as well as moisture and corrosion detection are discussed.

Keywords

Nondestructive testing, civil engineering, geophysics.

1 Introduction

Geophysics and Civil Engineering are strongly connected. Despite the fact that much larger budgets are spent in hydrocarbon exploration and the search for mineral resources, geophysical methods have been applied and accepted on civil engineering projects since decades. Obviously the focus has been on geotechnical projects – using geophysical methods to investigate the often complex and changing subsurface as a base for large engineered structures such as dams, bridges or buildings.

This review and outlook focuses mostly on structural investigations covering all kinds of elements between quality assurance of foundations to long term bridge monitoring. For more than 25 years methods as ground penetrating radar (GPR) and various seismic techniques have found regular applications here. Some geophysical methods are even part of standards and recommendations. Other methods (e.g., self-potential) have been developed and applied in both disciplines separately and sometimes under different names. Recently several modern geophysical methods have been adapted to structural investigations in various fields. They help to improve the quality of imaging the interior of structures and to detect small changes in concrete. The other discipline which has a (probably much stronger) influence in this area is non-destructive testing of steel and other metals, well established and mostly standardized for a long time. However, both fields are based on the same physical and mathematical principles even they used different wording, tricks and shortcuts.

2 Current Applications of Geophysics in Civil Engineering

2.1 Geotechnical Applications

To no surprise geophysical methods play an important role in many geotechnical projects as the objective under consideration is the same as in other geophysical filed as exploration and seismology: characterize the soil, rock and groundwater. Of particular interest in geotechnical site investigations is the characterization of the mechanical properties of soil and rock, such as shear modulus, bulk density, porosity, as well as the lithology and patterns of fracturing and weathering, e.g., fracture orientation, depth to bedrock, fault location. Seismic methods are the most well established approach, with electrical resistivity and electromagnetic techniques gaining in popularity.

Early methods and applications have been compiled by Ward [1]. A more recent overview is given by Reynolds [2]. Momayez et al. [3] collected several papers showing today's state of the art in their joint JEEG-NSG special issue on Geotechnical Assessment and Geo-Environmental Engineering Geophysics. After some disastrous flood events a lot of research was performed especially on river embankment investigation, as published e. g. in [4][5][6][7][8].

Typical applications of geophysical methods include but are not limited to: Detection of bedrock and groundwater level, delineation of different subsurface materials (e. g. sand. vs. clay) or detection of "weak" material as peat or slide planes. From a geotechnical engineer's point of view the determination of certain geotechnical design parameters such as shear strength, bulk density, permeability, porosity, shear modulus and others are most important, as they have to be used in standardized calculations for earthwork or foundation design, landslide protection or earthquake engineering. In fact only one of the parameters appearing in geotechnical standards can directly be delivered by geophysical methods: The average value of the shear wave velocity of the uppermost 30 meters (V_{s30}) is a core parameter for risk assessment in earthquake prone areas (e. g. in Eurocode 8). For all other parameters local relationships have to be established, requiring borehole, sampling and lab investigations. These relationships are in most cases complex and nonlinear. Recently published studies using geostatistical approaches may lead to a breakthrough in this field (e. g. [9][10]).

Some geophysical techniques have been standardized in the past, even if some of them seem to be a little simple or outdated from the point of view of an exploration geophysicist. ASTM standards include for instance methods as downhole or crosshole seismics which have been substituted in geophysics by multi-offset vertical seismic profiling (VSP) or crosshole tomography, respectively. But it has to be taken into account, that only methods included (or at least mentioned) in standards will find their way into regular application in civil engineering.

2.2 Geophysical Methods in Structural Investigations

The most popular method adapted from geophysics to civil engineering is ground penetrating radar [11] as it allows to detect small features in construction. GPR allows the detection of rebar and other elements at depths greater than those accessible by conventional eddy current instruments and provides better detections rate for metallic objects than ultrasonic methods. GPR manufacturers and suppliers of civil engineering measurement technologies have developed devices, antennas and software specifically adapted to the inspection of reinforced concrete elements. User interfaces dedicated to non-experts are claimed to allow the use by technicians and engineers after a short training period.

Spectral Analysis of Surface Waves (SASW) has gained a lot of interest and commercial applications in the last 15 to 20 years, mainly triggered by its extension to MASW (Multistation Analysis of Surface Waves, [12]) which allows effective pseudo 2D imaging of shear wave velocity and thus the dynamic low strain shear modulus. However, in civil engineering the application is mostly limited to pavement analysis [13] and less popular in structural investigation of concrete. Recently the investigation of refractory material has received attention [14].

The self-potential (SP) method [15] is a good example of a method pursued in geophysics and civil engineering in parallel almost without scientific exchange. Geophysical applications include the exploration for near surface ore bodies, the detection of groundwater flow and environmental contaminations. In civil engineering SP (name in civil engineering is half-cell potential, e. g. [16]) is used to detect corrosion of steel rebar in reinforced concrete. Applying the method is a standardized task, e.g. in the investigation of parking garages or bridge decks, which are affected by deicing salts. Methods from (passive) seismology have found application in civil engineering as well too. However, most of them are still in research stage. Some examples include monitoring of concrete structures by seismic interferometry using ambient vibrations or using coda wave interferometry to detect small changes in concrete. These applications are discussed later in this paper. Recent advances in microseismic event localization are finding their way to structural investigations as well

to improve the results of the established acoustic emission (AE) techniques for crack event detection (reviewed recently in [17]). One example is using deconvolution to focus energy in time reversal techniques [18].

3 New concepts

3.1 Advances in wave based imaging

Sophisticated methods for imaging using elastic or electromagnetic waves have been introduced to geophysical hydrocarbon exploration in the last decade. Some of them have extended capabilities compared to the state of the art in ultrasonic or GPR echo testing of concrete constructions. Unfortunately these techniques require significant computing time. However, some first successful examples for the use of Reverse Time Migration algorithms for ultrasonic data have been published recently [19][20][21]. The potentially even more powerful (but also even more computationally intensive) technique of full waveform inversion was adapted to GPR investigations of concrete [22] and masonry [23].

3.2 Quality Assurance in Foundation Engineering

Checking foundations element for geometry integrity and durability is of major concern as these objects (or at least most part of them) are not accessible for visual inspection or sampling. Calibration of non-destructive tools is an issue as well. Recently certain type of underground construction elements have been investigated by geophysical methods. Techniques from vertical seismic profiling and general geophysical data processing have been used to improve integrity testing of foundation piles [24][25]. Other authors focus on resistivity and seismic techniques to determine the diameter of jet grouting columns [26][27].

3.3 Detecting small changes in construction materials

Concrete is generally considered to be a durable material. However due to several damage mechanism the life span may be reduced from decades or even centuries to a few years. Among these mechanisms are dynamic influences (traffic, wind, earthquakes), alkali silica reaction or freeze thaw effects. Most structures are very resilient to these impacts, but some require monitoring. As most of the damages start very subtle and almost invisible they may be detected by conventional means only when repair or rehabilitation is already expensive. In the last years methods from seismology have been adopted to concrete monitoring. Among them are passive seismic interferometric techniques evaluating the behavior of an entire structure [28][29] and active techniques based on ultrasonic transmission (coda wave interferometry), some of them even tomographic [30][31][32]. Passive seismic interferometry has recently been used to characterize progressive damage in earthen embankments and levees [33]. Using nonlinear ultrasonic techniques has so far being limited to the laboratory, but can be expected to play a significant role in the future.

3.4 Moisture and corrosion detection

Detecting water in the subsurface and determining related properties as porosity or permeability has been a focal point in engineering geophysics since decades. In particular, resistivity and associated techniques as complex resistivity got a lot of attention. But until now practical application on concrete and other structural materials was mostly limited to simple fixed spacing Wenner array mapping surveys including qualitative interpretation only. However, experiments with tomographic approaches go back until the mid 1990ies (e.g. [34]). Recently more multi electrode surveys and 2D/3D inversion techniques have been used in concrete investigation. For example they have been applied in laboratory studies for structural investigation [35], corrosion studies [36] or crack detection in massive structures (using boreholes, [0]).

Complex resistivity, which is an extension of the traditional resistivity method into the frequency domain (1 mHz - 1 kHz) with the potential to give further insight into pore scale properties, was e. g. used to follow the effects of flooding and the subsequent drying on masonry [37]. Higher frequency methods (impedance spectroscopy, IS) are used for early age mortar and cement paste studies since decades. Recently a study on the influence of moisture and ions on mortars using IS was published [38].

4 Outlook

We think that there is much headroom to improve the interdisciplinary cooperation between geophysics and non-destructive testing in civil engineering (NDT-CE). The application of novel methods from geophysics would help to overcome current limitations e. g. in imaging small structures or subtle changes. On the other hand measurements on concrete structures might serve as scale experiments to validate geophysical algorithms or simulation methods.

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