

A review of non-destructive methods applied in deep foundations

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Abstract. In the field of civil engineering, non-destructive methods occupy an essential place at the heart of each major project or planned civil engineering work. Among the several applications of this technique, one finds the quality control of various elements constituting the structure of the work (concrete, reinforcement, steel ... etc) as well as the recognition of pathologies. Of main interest in this context, non-destructive based methods allow for quality monitoring during construction and inspection of defects during and after the works, especially in inaccessible sites (piles, deep foundations, nuclear sites). Secondly, the preventive and corrective maintenance of old infrastructures can gain in efficiency thanks to the detection of failures and accurate localisation of damaged parts which are provided by this technique. It is in this perspective that the present research project focuses on the detection of failures that occur in deep foundations by means of a non-destructive testing method. A critical analysis is adopted and various methods were explored along with their principle, advantages, limitations and fields of application.

1 Introduction

Each foundation is made up of elements such as concrete, steel, etc. These materials are the most common used during the process of construction. Besides their many advantages, they are known to evolve and react with their environment. Consequently, over time, reinforced concrete foundations develop many pathologies (corrosion of steel, freeze-thaw, creep, chemical reactions,...). Under the action of these physical-chemical aggressions, the latter degrades and presents disorders ranging from simple cracks to serious structural deterioration [1].

Today, non-destructive testing (NDT) based methods play a key role and are one of the most suitable ways to achieve high performance evaluation of structures such as reinforced concrete foundations. NDT makes it possible to give quantitative information on the whole of the examined specimen while limiting the number of required samples. Thus, it provides us more effectively with essential information about the structural performance of the foundation [2]. This include dimensions of the elements, location of cracks, delaminations and disbands, degree of consolidation, presence of voids and honeycombing, location and size of steel reinforcement, corrosive activity of the reinforcement, extent of damage caused by freezing and thawing, fire or chemical exposure and actual strength of the concrete.

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2 Classification of non-destructive methods in deep foundation

2.1 Types of classification

Non-destructive methods can be classified according to several criteria [3]:

- The nature of the non-destructive technique itself (internal, external, remote).
- The element prospected to which the non-destructive method is applied (surface control, volume control).

But the most famous and distinguished classification is the one which is based on well-known physical principles [1-3], therefore we can classify the different non-destructive techniques into several families according to their related physical branches.

2.2 Assessment of existing methods

2.2.1 Seismic method

Seismic method is one of the main methods of non-destructive prospecting. It is essentially based on the time or frequency analysis of mechanical waves that can propagate through or on the surface of the inspected element. The mechanical wave propagation technique

allows for examination of the maturity materials such as concrete and serves to determine its homogeneity and to detect eventually defects (cracks, voids, etc.). They are sensitive to mechanical properties (compressive strength, modulus of elasticity) as well as to certain physical properties (saturation, porosity).

There are two types of seismic methods according to the mode of propagation of waves: surface reflection and direct transmission [1]. Each category contains in its turn many methods as shown in Fig.1.

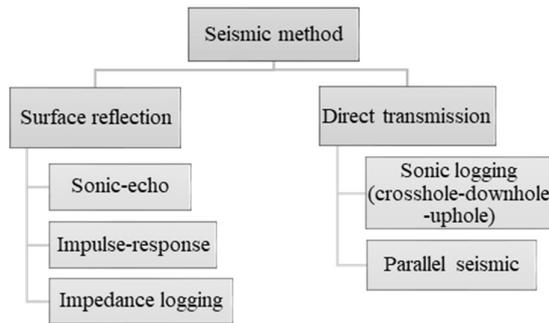


Fig 1.Types of seismic based methods.

Table 1. Advantages and limitations of seismic based methods.

Seismic method	Advantages	Limitations
Sonic-echo	-No pre-installed tubes -Portable equipment	-Can confuse necking and bulging -Does not measure diameter -Does not measure length or detect irregularities in lower portions of shafts
Impulse-response	-No pre-installed tubes -Measure stiffness -Portable equipment	-Requires a well-trained technician for interpretation -Similar limitations as sonic-echo
Impedance logging	-Portable equipment -Effective geometry of the foundation can be obtained from the analysis of the signal	-Analysis requires a well-trained technicians -Requires analysis offsite - Accurate analysis necessities good test data
Sonic logging	-Can function at any depth -Detection of irregularities between tubes is more accurate than in surface reflection	-Requires pre-installed tubes or coring -Irregularities at edge of shaft cannot be detected
Parallel seismic	-Accessible -It is useful when direct access to the head of foundation is impossible -Existing foundations can be inspected - Not sensitive to soil damping as for surface reflection methods	- Requires preinstalled hole adjacent to the foundation - Could not recognize small defects

The common factor of all the seismic based methods is that they are fast and they have the ability to determine efficiently the localisation of defect in deep foundation. Table 1 summarizes the inherent advantages and limitations of each one of these method [1, 3-8].

2.2.2 Visual inspection

Visual inspection is the primary way for non-destructive testing. It can be used for the recognition and diagnosis of reinforced concrete in foundation, allowing to provide immediately useful and global data on the degree of visible deterioration, such as spalling of concrete surfaces, appearance of cracks and defects, advanced corrosion of reinforcement's steel, ... [2].

Visual inspection can be divided into two categories: direct using direct vision and indirect using tools and machines. Related to this part, several technological advancements have influenced this field from simple magnifying glasses to more expensive hand-held microscopes and sophisticated cameras [9-10]. But the application of direct vision in deep foundations remains somewhat limited due to the impossibility of visualizing the deep parts. It can only visualise the top surface of foundation. This obstacle can be overcome by digging an adjacent borehole to the foundation, and using specific tools and cameras [11]. Among the advantages of this method one can find the following:

- Low cost,
 - No need for sophisticates equipments.
- As for limitations, there are:
- Only visible surfaces can be inspected,
 - Internal defects cannot be informed,
 - No information about concrete and reinforcement proprieties,
 - It requires one or more supplementary NDT methods.

2.2.3 Electrical method

Electrical methods are often used to characterize and evaluate the state of the reinforced section of the foundation. These methods are based on the measurement of the electrical resistance. The principle consists generally in measuring the potential difference between two electrodes, with fixing the foundation reinforcement (generally pile) as one electrode and the soil as another [12-13].

The two factors that influence the result are the electrical resistance of the concrete (R_c) and that of the soil immediately surrounding the pile (R_s). It is important, therefore, that the differentiation between these two values should be large, the more the ratio of R_c/R_s is close to one, the more this method is not effective [3].

Four types of electrical method can be defined [3,14]:

- Resistance to earth,
- Self-potential,
- Resistivity testing,
- Induced polarisation.

The advantages of the electrical method are:

- Light and mobile devices,
- Provides an indication of the possibility of corrosive activity,
- can be used on freshly cast foundation.

While the limitations include:

- Very limited in term of depth,
- Requires a well-trained technician for interpretation,
- Required a connection to reinforcement, which should be electrically connected,
- No standards for different test systems and difficulties for interpreting test results,
- For induced polarisation, concrete surfaces must be smooth, free of grooves, free from impermeable coatings and free from visible moisture,
- For induced polarisation, different devices give different values of corrosion rate.

2.2.4 Nuclear method

By reason of its radioactivity danger, nuclear inspection is one of the rarest non-destructive methods applied in inspection of structures. Nuclear method consists in measuring the atomic particles emitted from a radioactive source and captured by a receiver, both installed in the material forming the pile (pre-installed tubes) [3].

There are two types of nuclear particles: gamma ray and neutron. Regarding gamma ray based techniques, the longer the distance travelled from emitter to receiver or the greater the density of the material, the higher is the amount of absorbing source particles or scattered. Since the distance between the emitter and the receiver is fixed during the test, the observation counting rate is therefore depending on the density of the material through which radiation is crossing. Moreover neutron techniques depend on the fact that neutrons emitted from the source are slowed quickly by the presence of hydrogen atoms, this "slow" neutron detection is mainly a measure of hydrogen's presence in the material, or equivalently the presence of water in the concrete [3].

Three categories of nuclear based methods can be distinguished [1,3,6] :

- Neutron backscatter,
- Gamma-ray backscatter,
- Gamma-ray transmission (cross hole gamma-ray or gamma-gamma logging).

The advantages of nuclear based methods are:

- Light and mobile devices,
- Fast testing,
- Can evaluate fresh and hard concrete.

The limitations include:

- Imminent danger of radioactivity,
- Necessity of pre-installed tubes,
- Operators must be licensed,
- Precision of backscatter technique is lower than direct transmission,
- Measurement can be affected by material closer to surface,
- Sensitive to chemical composition.

2.2.5 Electromagnetic method

This method is based on the sensitivity of electromagnetic waves to the nature of the propagation medium. It consists generally in emitting a high frequency electromagnetic pulse which propagates and is partly reflected at each interface between two different electromagnetic media. This is why this technique makes it possible to quickly locate cavities, detect reinforcement, defects (voids, honey combing) in concrete [15-16].

Ground-penetrating radar (GPR) is one the available electromagnetic methods that can be applied. Various configuration of this testing method are found in practice. Among them, one finds the variant that is more suitable for foundation and which requires two opposite boreholes. The transmitter antenna will be located in a borehole, while the receive antenna will be located in the borehole on the opposite side of the deep foundation (generally pile). Thus, the radar pulse propagates from the transmitting borehole, through the deep foundation, to the receiving borehole. To simplify tomography calculations, generally cross bore-hole GPR data are stored as a sequence of discrete measurements or samples, spaced at 0.25 m vertically intervals [6].

Advantages of the electromagnetic method include:

- Provide a fast scanning,
- Locate with precision the defect,
- Sensitive to the presence of moisture and chemical compositions,
- Sensitive to the steel reinforcement.

The limitations can be:

- High resolution equipment is expensive,
- Pre-installed borehole,
- Operators must be trained and experienced,
- Cracks and delaminations are so hard to find,
- Large amounts of data obtained during scans with necessities post-processing and interpretation,
- Absence of method standards.

2.2.6 Osterberg cell

The Osterberg cell (o-cell) method is named after his inventor Osterberg. It consists of a metal piston and a cylinder that can be actuated by an expandable chamber containing a compress liquid (oil or water). Each piston and cylinder is welded to a thick steel plate with a maximum diameter of approximately the diameter of the tested pile. The piston undergoes the action of the compress fluid, and since pistons are typically at least 800mm in diameter, large loads can be applied by the Osterberg cell for low hydraulic pressures. 2700tons loads can be achieved with the largest cells [5-6].

Once concrete is going hard, the jack is injected, creating both an up and down force in the shaft. Depending on where the cell is located in the pile, load tests can be performed, allowing getting information about pile bearing capacity and, at the same time, about the load distribution to pile base and shaft [17-18].

The advantages of this method are:

- Provide pile bearing capacity,
- Provides distribution of pile bearing capacity,
- Measure the side friction on the shaft,
- Potential of improvement.

The limitations can be:

- Expensive cost,
- Pre-installed mechanism must be placed before casting concrete,
- Operators must be trained and experienced,
- No information about localisation of defects,
- No information about cracks and delaminations.

3 The criteria for choosing the non-destructive method to be used

With a variety of methods that are available, the first question that needs to be answered is: which test or combination of tests would be best suited to the problem or situation control? For responding to this question the following criteria must be taken into account [3]:

- One should make out whether the method is suitable for the foundation system,
- The ground conditions are appropriate with the method or not,
- The level of supervision of the foundation construction,
- The level of efficiency of the investigation method,
- The cost of the investigation method,
- Before starting the foundation, there are problems related to the ground or the foundation, and that the proposed method could identify,
- The availability and relevance of information on the foundations construction, such as the volume of concrete used to form the foundations, stops in the construction process, other observations and measurements...,
- Aspects linked to the suitability of the selected type of investigative technique in relation to different foundation defects, as discussed in Section 2 of this paper.

4 Conclusions

Various non-destructive testing methods that are applied in field inspection of deep foundations were reviewed in this work. These included seismic, electrical, electromagnetic and nuclear based techniques. The evaluation was performed in terms of their advantages, limitations, technical feasibility and relevance to foundation systems. Adapting the inspection method to a given situation should consider the expected properties of the examined foundation such as concrete viscosity, concrete compression resistance and soil bearing capacity. Accessibility is also an important aspect to deal with in practice. It was found that the most important facts that differentiate between the different investigations techniques are:

- The level of relevance of the desired results,
- The possibility of in situ implementation of non-destructive test and the ease of data processing,
- The cost of non-destructive testing.

Some recommendations were proposed about which test suits the best a given inspection situation.

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