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Non destructive tests to detect the integrity of steel anchors in corrosive environments

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***Abstract* –Metal-tensioned systems like bar or strand anchors may lose efficiency and eventually reach failure due to corrosion caused by aggressive ground conditions or stray currents. Early recognition tests capable of highlighting the loss of performance would enable to undertake remediation before these effects become catastrophic. The paper analyses the efficiency of different non-invasive techniques adopted to assess the continuity and the geometric shrinkage of metal bars. A review of the literature is initially made to illustrate potentials and defects of the different solutions providing a one-dimensional propagation of waves along slender elements. Then an experimental set-up is created in the laboratory to evaluate the effectiveness of a ultrasonic vibratory wave system with bench tests on bars of various geometrical and mechanical characteristics. Defects such as cross sectional reduction, artificially simulated on the bars, are highlighted by the analyses of the recorded signals.**

I. INTRODUCTION

Metal elements like bolts, anchors or nails are currently used in several geotechnical engineering applications to provide temporary or permanent reinforcement to soil or rock slopes. The application of bolts in the mining industry dates back to the early sixties of the past century [1]. Later on, from the seventies to date, permanent ground anchors are being extensively used in civil engineering, mostly in transportation project, to support natural walls, trenched excavations or tunnel canopies or to guarantee the stability of cut slopes. Some meaningful examples of reinforcement are listed in Fig.1 where steel elements are used to pre-stress foundation embankments [2], as tiebacks of earth retaining structures [3] or as to stabilize of natural or artificial rock or soil slopes [4]. In all cases, bars or strands of variable length are buried in the subsoil. Reinforcement can be passive, when tensile and shear forces are activated in the metal rod just by movement of the surrounding mass, or active when the bars or strands are pre-stressed to infer additional compressive stress and frictional resistance to the surrounding material. Rather frequently reinforcement

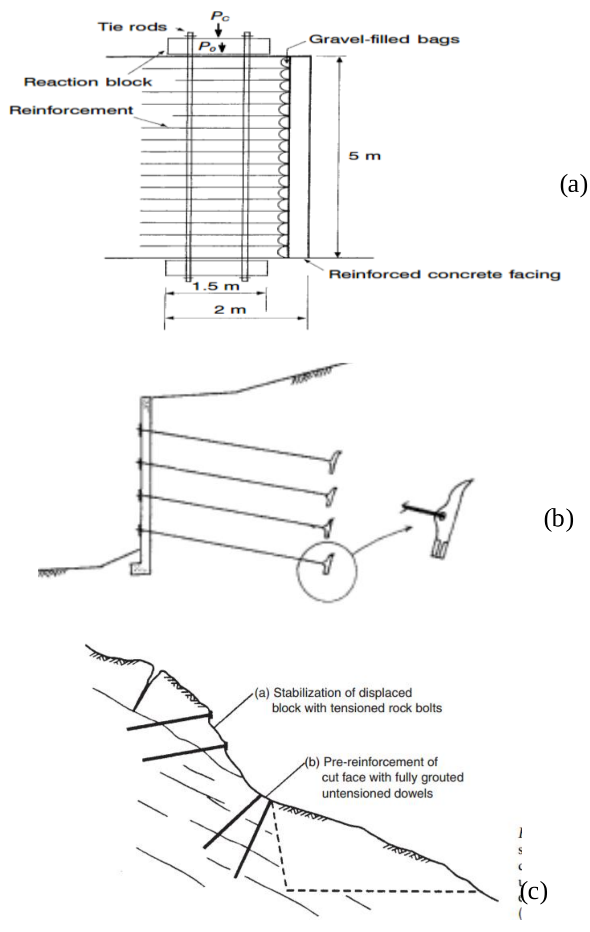

Figure 1. Examples of metal reinforcement in geotechnical engineering - a. foundation embankment [2]; b. earth retaining wall [3]; c. rock slope [4].

lies in particularly aggressive conditions, given by chemical aggressive agents present in the pore water, or by stray currents circulating in the closest environment. In particular, stray currents generated by unbalanced electrical supply systems or wiring flaws find their

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preferential path through metal immersed in the ground, producing electrical potential on elements that should not undergo voltage. This phenomenon, developing at speeds ruled by the local electrochemical conditions may produce minor nuisance or, in the most severe cases, trigger the complete corrosion of the metal [5]. In the latter case, the restricted cross section of the metal elements become progressively unable to withstand tensile loads. If the phenomenon takes place simultaneously in a large number of close reinforcements the stability of the whole geotechnical structure is impaired and catastrophic effects may result.

Typical mitigating countermeasures consist in insulating the metal elements by epoxy protective coats or in the adoption of cathodic systems or galvanic discharge [6]. However, a periodic control of the reinforcement should be planned to be aware of the serviceability life of the supporting system and prevent risk before extreme casualties occur. The effectiveness of visual inspection on the element head assembly is uncertain and not indicative of ongoing problems, as corrosion takes place slowly and locally. On the other hand, mechanical pull-out tests are costly, time consuming and invasive, and cannot be performed extensively on the whole structure, but just on few sample elements. Hence, transportation agencies, faced with the task of allocating budgets to maintain facilities, may take significant advantage from tools capable of assessing the remaining useful service life of supporting systems with fast and reliable tests. This paper presents the first results of an ongoing research conceived to develop a non invasive system to evaluate the integrity of buried metal systems. After presenting different categories of nondestructive tests, the experimental setup of a system based on vibratory excitation is described together with the preliminary results obtained on samples of different material and dimensions.

II. NON INVASIVE DETECTION

The non destructive techniques to detect the corrosion of metal strands or bars can be broadly distinguished in electric and mechanical measurement techniques, the former implying the migration of electric current, the second based on the propagation of sonic waves.

Electric measurement

- *Corrosion Potential Mapping*

The basic principle of this method [7] consists in measuring the corrosion potential of the buried rod, comparatively with a reference electrode of known characteristics (copper/copper sulphate). In this way, the probability of the metal rod to corrode is evaluated, identifying the incipient tendency before its effects become visible. A periodic investigation, extensively performed over all anchors of the supporting structure, allows to soon identify elements prone to corrosion, evaluate the extent of the phenomenon even with statistical analyses and prioritize remediation. On the other side, this method does not allow to quantify local defects such as cross sectional restriction, as it assumes that corrosion acts uniformly over the whole element.

- *Polarization measurement*

With this method, often used in combination with the previous one, a known voltage is applied between the metal element and the ground bed and the relationship between surface potential and impressed current is measured. The electric current flows through the soil/water electrolyte from the element to the ground bed, as function of the applied voltage, and negatively charged ions migrate through the soil/water electrolyte. Polarization measurements are then correlated with the surface area of bare metal in contact with the ground. In this way, complete cutting of the buried rod may be soon revealed by a reduction of flowing current. On the other hand, small local restriction of the metal rod caused by corrosion cannot be identified.

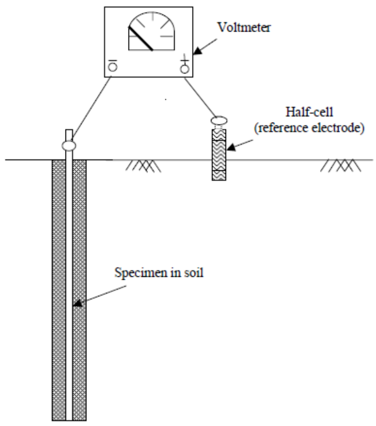


Figure 2. Scheme of the mapping of corrosion potential.

Mechanical measurement

- *Impedance test*

With this method the coupled anchor - rock system is forced to oscillate with button sinusoidal of variable angular frequency and amplitude applied from the head. The maximum speed is measured at the rod head and the curve describing its dependency on the applied angular pulsation is built. The distance from consequent peaks is indicative of the stiffness of the system, and consequently of possible physical and structural defects.

- *Impact tests*

This test evaluates the propagation throughout the investigated element of pulse dynamic waves excited from its head with a hammer or ball device [8]. The same principle is used to investigate the small strain of soils [9, 10] Elastic compression/extension waves with relatively low frequency content are generated at the head of the rod, travel forth and back through it and are recorded by a sensor placed near the impact point. Most typically the sensor consists of an accelerometer, even though velocimeters and displacement transducers are sometimes used. As travelling time is related to the elastic stiffness of the material and travel length, the former property is firstly calibrated by measuring the travel time on integer elements of prescribed length. Thereafter, since waves are reflected whenever a change of material properties or geometry occurs along the length of the tested element, the interpretation of the signal gives an indication of its integrity of the metal elements. In fact, local restrictions cause the excited wave to be partly reflected, and so their presence is shown by the anticipated arrival of waves to the sensor. Interpretation of measurement may be performed in both time and frequency domains.

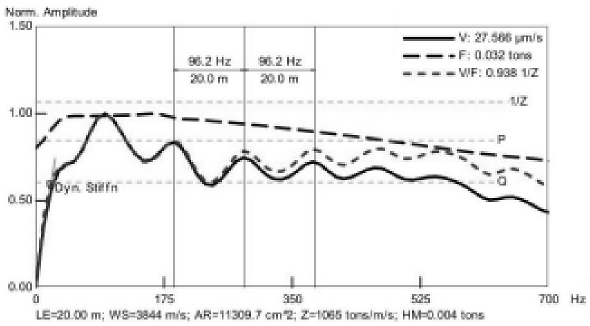


Figure 3. Typical result of impedance test.

- *Ultrasonic wave test*

The basic principle of this technique is similar to the previous one, with the difference that waves of prescribed frequency content are generated by sensor connected to a generator of function giving prescribe voltage. The travel time can be obtained comparing the time history of the signal given at the source with the one recorded by the receiver. A better interpretation can be obtained by studying the cross correlation between the two signals. Other interpretation tools can be added, such as those based on neural networks [11], initially trained to relate the recorded signal to known defects and then used to forecast the defect type based on measurement.

This system has been implemented in the present study with the characteristics described in the following chapters.

III. THE EXPERIMENTAL SET-UP

The authors, starting from their experience in realizing probes and experimental set-ups in the field of non-destructive testing and component characterization [12-15], have realized a suitable experimental set-up to verify the suitability of the proposed measurement idea. In the following details are given for both the instrumental set-up and the choice of the excitation signals.

A. The Instrumental Set-Up

A block diagram of the instrument set-up is reported in Fig.4. It can be divided in four sections: i) the ultrasound section, ii) the conditioning section, iii) the signal generation and data acquisition section, and iv) the signal processing section.

The section i) is composed of a couple of Olympus Videoscan V109RB™ ultrasound transducers. Both are placed on the head of the tested specimen, one to excite the ultrasound signal, the other to detect the received echo. They are contact-type transducer with a central bandwidth of 5.00MHz and an element diameter of 1.25cm. The shape of the transducer and its main sensitivity are respectively reported in Fig.5 a) and b).

The conditioning section ii) is composed by two amplifiers. In detail, a variable gain single channel instrumentation amplifier, namely the Analog Device AD8331™, allows up to 44 dB of magnification for the received ultrasound signal with a bandwidth up to 12 MHz, while a fixed 50x amplifier, namely the Falco System VMA-320™, allows the magnification of the injected ultrasound signal up to +/- 150V with a bandwidth of 5 MHz and a maximum current of 300mA and a reduced noise of 12 mV RMS over the whole band.

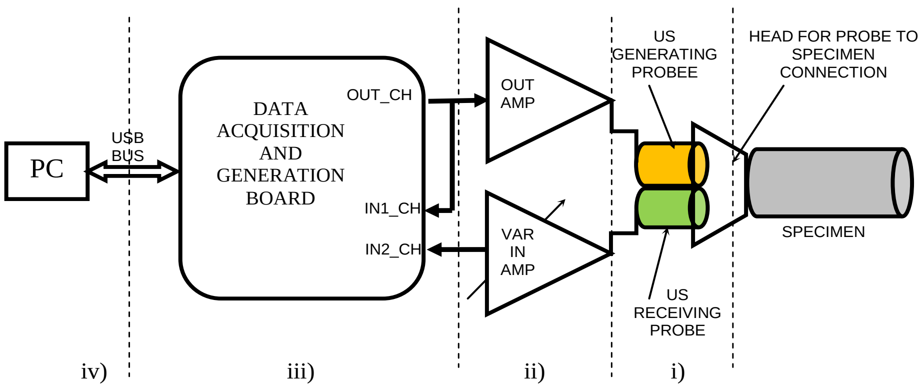
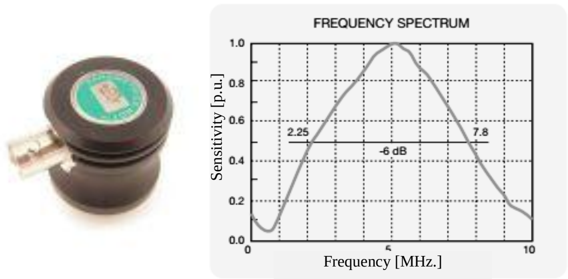


Fig. 4. The realized measurement set-up: the four measurement sections are highlighted .



a) b)

Fig. 5. The adopted transducer: a) picture and b) frequency characteristics.

The signal generation and data acquisition section (iii) is made of a single board generation and acquisition system (TIE PIE Engineering Handyscope HS5-540XMS-W5™) with USB data connection. As for the acquisition section, this system allows fast sampling up to 500 MS/s with a best resolution of 16 bits and a memory of 64 MSamples. The acquisition system supports continuous streaming measurements up to 20 MS/s and can be synchronized with other oscilloscopes. As far as the generating section is concerned, a built-in 40 MHz 14 bit Constant Data Size (CDS) arbitrary waveform generator with 24 V peak to peak output is provided.

The signal processing section iv) has been designed in Labview™ environment. It aims to create and upload the arbitrary waveforms to the source ultrasound transducer, record the generated and received signals and comparatively process them to retrieve the measurement information (see Fig.4). As far as the measurement algorithm is concerned, it is based on the analysis of the cross-correlation function estimates.

B. The arbitrary excitation signals

The choice of suitable excitation signals is a key issue in ultrasonic NDT. In particular, some constraints have to be considered. They concern with: a) the frequency of the considered signal that has to be in compliance with the frequency characteristics of the ultrasonic probes and with the sound propagation in the considered material; b) the time delay of the echo signal with respect to the injected signal that depend from the considered material and its maximum length; c) the overall energy associated to the signal that has to produce echoes of suitable amplitudes; d) the suitability of the signal to produce measurement information from the received echoes.

In the considered case the ultrasonic probes have a central bandwidth of 5 MHz with usable frequencies in the 1 MHz to 10 MHz and the considered material has a mean sound propagation speed of 5000 m/s and length up to 1.5 m. This implies that the inject ultrasound signal takes about 0.6 ms to produce an echo. To this aim the considered injected ultrasound signal must ensure frequencies in the range between 1 and 10 MHz and duration greater than 1 ms.

Taking also into account the above considered requirements c) and d) and the maximum power provided by the considered measurement station amplifiers impulsive and sinusoidal signals cannot be adopted.

After a number of experiments, not reported here for brevity, a linear chirp signal has been provided to the transmitting ultrasound probe.

The Linear Chirp signal is one of the most used waveform used in pulse compression applications such as radar, sonar, spread-spectrum communications, etc. and it is described by the general expression: $s(t)=\alpha(t)\sin(\Phi(t))$ where $\Phi(t)=2\pi(f_1 t+\frac{f_2-f_1}{2T}t^2)$ is a quadratic phase term ensuring that a linear varying instantaneous frequency $f_{ist}=f_1+[(f_2-f_1)\times t]/T$= $f_{ist}=f_1+(Bw\times t)/T$ is obtained, $Bw=f_2-f_1$ is the bandwidth of the chirp, T is the duration of the chirp signal and $\alpha(t)$ is a windowing function (i.e. rectangular in the present case) that is not-vanishing only in the chosen time interval. This warrants a constant envelope and an almost flat power spectrum in the spanned frequency range $f\in[f_1,f_2]$. More generally, different windowing functions can be used to modulate the amplitude of s(t) and, due to the characteristic of linear chirp, also of the power spectrum.

The chirp approach allows the simultaneous analysis in

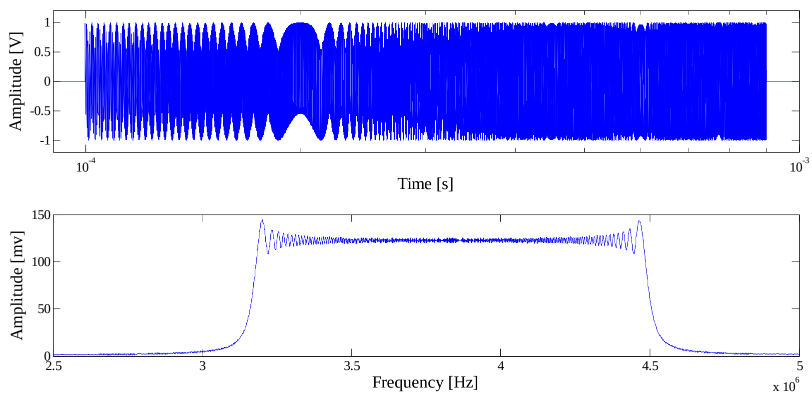


Fig. 6. The realized exciting signal: the upper figure describes the time behavior on a logarithmic scale; the lower figure describes the frequency characteristics.

Fig. 7. A photo of the experimental set-up: the specimen under test with the connected ultrasound transducers are highlighted with a red circle.

both time- and frequency- domain, and it can provide complementary information about defects and a better robustness against the noise, improving both the identification of defects and the capability of characterization.

In order to infer enough input energy to all the given frequencies and contemporarily to guarantee effectiveness of the pulse compression procedure, the choice of the actual chirp parameters values has been: Bw=1.5 MHz (f1= 3 MHz, f2=4.5 MHz), T=1ms, T×Bw~1500. Fig.6 sketches the main characteristics of the generated signal.

IV. EXPERIMENTAL RESULTS

A number of preliminary experimental results are has been performed on a specimen consisting of a steel bar used for reinforced concrete. The bar has diameter equal to 3 cm and length of 1.11 m and is made of class 316L steel having tensile strength=590 N/mm^2, Young's modulus= 200GPa and density=7850 kg/m^3.

The first test was run to check the suitability of the method, the amplitude of the ultrasound signals, the optimal gain values of receiving amplifier and to retrieve experimental information about the sound speed in the specimen under test.

In this test, the transmitting and receiving ultrasound transducer are positioned at the two sides of the pole as highlighted in Fig. 7.

Twenty consecutive tests have been performed, giving results similar to that shown in Fig.8, where the input and recorded ultrasound signals (Fig.8.a and b) and the estimated correlation function (Fig.8.c and d) are respectively reported. A careful observation of Fig.8.b highlights that the recorded signal possesses the main characteristics of the input signal proving in this way that injected and received signal are correlated.

The correlation function shown in Figs.8.c and 8.d exhibit several local peaks, with the first located at 0.205 ms. However, the analysis of the whole test gives a mean value of the correlation interval equal to 0.2114 ms with an experimental standard deviation of 0.0053 ms. These results imply a repeatability of 0.1%.

Considering the length of the adopted specimen (1,11 m) a sound propagation speed of 5248.7 m/s with can be computed with an experimental standard deviation of 131 m/s (variation coefficient is equal to 2.5%).

Considering the density of material, this velocity corresponds to a confined stiffness moduli of 216 GPa (equivalent to a Young's modulus equal to 204 GPa and Poisson's coefficient ν=0.15)

A further test has been performed placing source and receiver on the same side of the steel bar, reproducing in this way this experimental set-up of in situ tests.

The obtained results reported in Fig.9 show results similar to those previously seen in Fig.8 except that the zoom of Fig.9.d reveals a maximum correlation at about

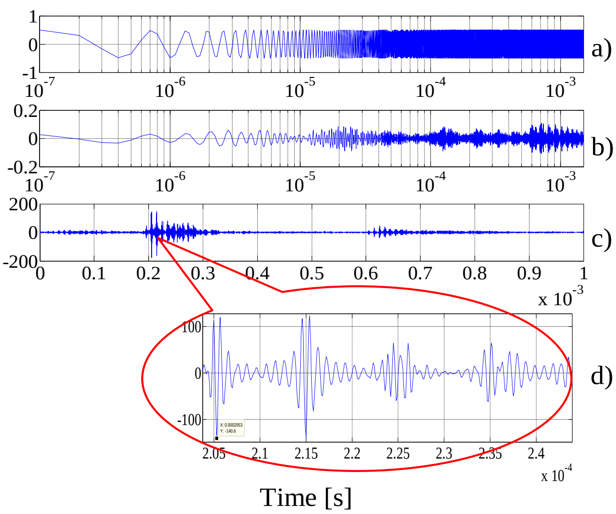


Fig. 8. Results of the first experimental test: . a) generated ultrasound signal, b) acquired ultrasound signal, c) correlation function and d) zoom near the maximum.

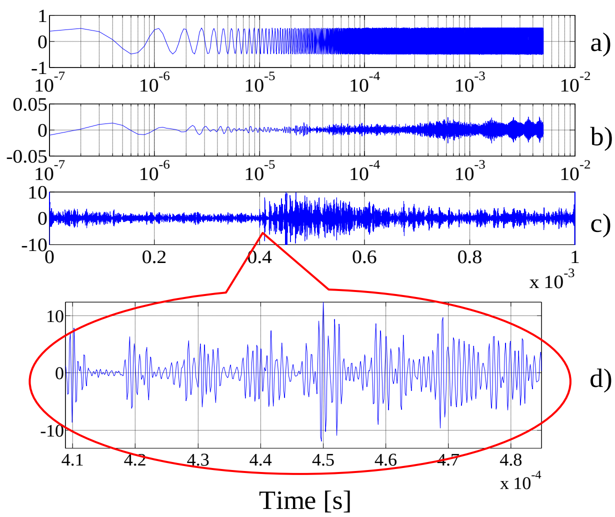


Fig. 9. Results of the second experimental test: . a) generated ultrasound signal, b) acquired ultrasound signal, c) correlation function and d) zoom near the maximum.

0.45 ms. A more complete analysis on the whole bar shows a mean value of the best correlation delay equal to 0.4401 ms with a standard deviation of 0.0070 ms (variation coefficient equal to 1.59 %).

Differently from the previous case of direct transmission, the presence of both transducers on the same side of the bar causes an echo located at about 0 ms. This is due to the change of ultrasonic impedance of the bar material with respect to the transducers and by an imperfect coupling between the two elements. The main echo is located at 0.4401 ms that, according to the previously measured propagation speed (5248,7 m/s), corresponds to a covered distance of 2.30 m. Considering that this distance is run by the wave to go forth and back along the bar, a length of 1.15 m is estimated for the bar, i.e. with an error of 3.6% on the real value of 1.11 m.

V. CONCLUSIONS AND FUTURE DEVELOPMENTS

This paper describes the experimental set-up and the preliminary results of an activity carried out to develop an ultrasound vibratory system aimed at detecting the effects of corrosion on steel longitudinal elements. The results of tests on a relatively short (1.11 m) stainless steel bar prove that the conceived system gives a reasonable estimate of the length, with an error of approximately 3.6% in excess to the real value. The preliminary experimental investigation must be completed, in order to have higher comprehensiveness and representativeness. Laboratory tests will be carried out on longer bars, i.e. more similar to true scale application, introducing local restriction, i.e. not causing complete interruption, to simulate corrosion. Finally, the experimental campaign will be concluded embedding the bars in soil or rock boreholes to simulate the real case of steel anchors or bolts.

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