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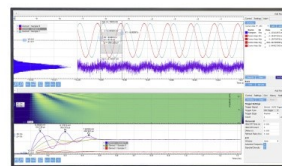
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Non destructive testing of concrete nuclear containment plants with surface waves : lab experiment on decimeter slabs and on the VeRCoRs mock-up

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Abstract. The maintenance and evaluation of concrete nuclear containment walls is a major concern as they must, in case of an accident, ensure the confinement of the nuclear radiations and resist to the loads. A homemade multi-receiver multi-source dry contact linear probe to record ultrasonic surface waves on concrete in the frequency range [60 kHz – 200 kHz] has been used in this context. The measurement protocol includes the summation of up to 50 spatially distributed seismograms and the determination of the surface waves phase velocity dispersion curve. The probe has been tested against several concrete states under no loading (water saturation level, temperature damage). Then, the same measurements have been performed on sound and fire damaged slabs submitted to uniaxial loading (stress up to 30 % of the concrete compression resistance). It is shown that the robustness and precision of the surface waves measurement protocol make it possible to follow the stress level. In March 2017 a first experiment with this surface wave probe has been conducted on a reduced 1:3 scale nuclear containment plant (EDF VeRCoRs mock-up) under loading conditions that replicates that of decennial inspection. The surface wave phase velocity dispersion curves of each state are compared and cross-validated with other NDT results.

INTRODUCTION

In the frame of French ANR project ENDE (Non destructive evaluation of concrete nuclear containment plants) several NDT techniques are benchmarked to determine which ones would be of interest in addition to existing inspection tools [1]. Within this general framework IFSTTAR has tested a homemade multi-receiver multi-source dry contact linear probe to record surface waves on concrete in the frequency range [60 kHz – 200 kHz] [2].

The sensitivity of this surface wave probe, called MACSYS, is here tested against stress. In normal operating condition the stress level in the nuclear containment wall is around 15 MPa thanks to a dense pre-stressing tendons network. Every 10 years a test is performed to check the tightness of the wall that consists in increasing the inside pressure up to 5 bars and to measure the air leakage from the outside. During this decennial test, the stress level in the wall is reduced to a value around 5 MPa. The level of stress variation which has to be followed is thus of the order of 10 MPa which corresponds to ultrasonic velocity variations less than a few percents. The challenge here is to get reliable quick surface wave measurements with an experimental set-up that is removed between each measurement capable to follow the stress level at specific points.

In this paper we describe a series of experiments that have been performed in the lab and then we show the first results obtained on a containment wall during a leakage test at the EDF VeRCoRs mock-up. The accuracy of MACSYS probe is proven to be effective in following stress variation corresponding to surface wave velocity variation lower than 1% even if the source and receivers are not glued to the concrete surface but dry coupled.

MACSYS SURFACE WAVE PROBE AND MEASUREMENT AND SIGNAL PROCESSING PROTOCOL

MACSYS probe has already been used with success to monitor water ingress in the lab [2]. The source central frequency is 100 kHz and the distance between two measurement points is equal to 0,05 m. The investigation depth is around 0,03 m. At MACSYS source central frequency concrete is an heterogeneous material [3]. A protocol, that has been validated in [2], consists in averaging 15 seismograms, randomly measured on a limited surface (typically of the size of the rebar mesh), to recover the coherent field thanks to summation of the individual seismograms. Here, to be able to follow modifications of the surface wave velocity lower than 1 % percents the averaging is increased over 50 seismograms. In that case, the measurement time, for one point, is equal to ten minutes.

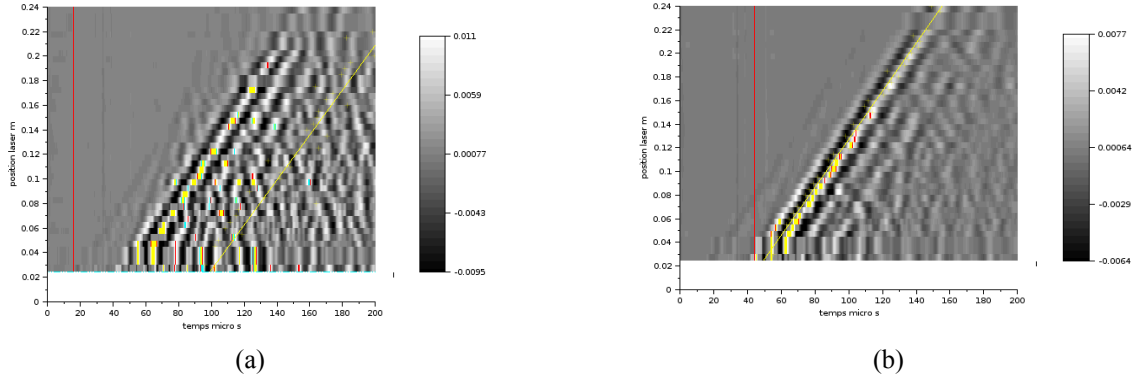


FIGURE 1. Seismograms measured on a 0,5 m x 0,25 m x 0,12 m concrete slab (a) individual seismogram, (b) average of 50 seismograms.

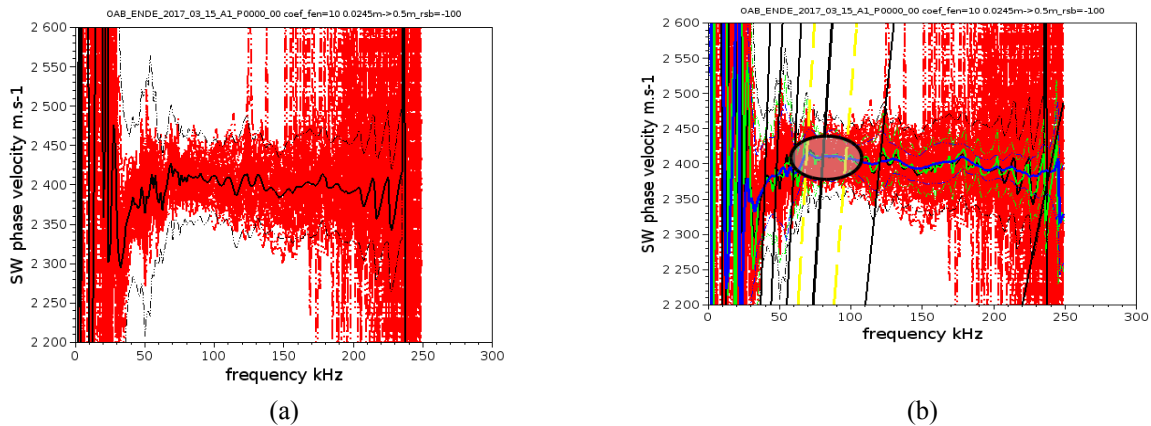


FIGURE 2. Phase velocity dispersion curves (a) of each 50 individual seismograms (fig. 1a) in red and the corresponding average in black, (b) of the average 50 seismograms (fig. 1b) before windowing in green and after windowing in blue. The black circle shows the phase velocity corresponding to a wavelength equal to 0,03 m (intersection of the dispersion curve with the thick sub-vertical black line).

To compute the phase velocity dispersion curve a p - ω transform [4] is used. Figure 1a shows one seismogram measure on a concrete slab. Figure 2a shows 50 individual dispersion curves obtained from 50 seismograms measured randomly in a square area delimited by the rebar mesh. The average of the 50 seismograms is shown Fig. 1b.

The surface wave coherent field is clearly visible in Fig. 1b making possible an automatic windowing of the surface wave train. The windowed average seismogram is used to compute the phase velocity of the coherent surface wave. This curve (in blue in Fig. 2b) is smoother than the average of the 50 individual dispersion curves (in

black in Fig. 2a). From the dispersion curve obtained (in blue in Fig. 2b) we extract the phase velocity corresponding to the wavelength equal to 0,03 m. Selecting a given wavelength ensures that we are always investigating the same depth which makes it possible to compare several states of concrete material under loadings.

This processing protocol is applied in all the following.

EXPERIMENTS IN THE LAB

A first series of measurements is performed in the lab on concrete slabs under static load. The slabs have the following dimensions: 0,5 m x 0,25 m x 0,12 m so that MACSYS probe can be used. The load is applied along the longest dimension of the slab (see Fig. 3 a drawing and a picture of a load frame). The concrete mix is similar to that of the VERCORS mock-up structure (CEM I 52,5, maximum aggregate size 19 mm, porosity 15 %, density 2350 kg/m³). The surface wave measurements are performed on the sides 0,5 m x 0,25 m large.

Experiment I

A first experiment is conducted on a slab that underwent thermal damage at a temperature of 150°C while under compression (10 MPa). After this damaging process the slab has been removed from the compression frame. The surface wave measurements described below are performed at a latter stage (several weeks after the damaging process).

The slab is installed under the loading frame (Fig. 3) and the load is increased from 0 kN up to 300 kN which corresponds to a maximum stress level (10 MPa) currently measured in on site nuclear containment wall. Three series of identical loading are performed. During the first two surface wave measurements are carried out on face B to verify the repeatability of the experimental set-up. During another loading the measurements are performed on face A. For those three loading no Kaiser memory effect is expected as the slab was beforehand already submitted to a load of 300 kN.

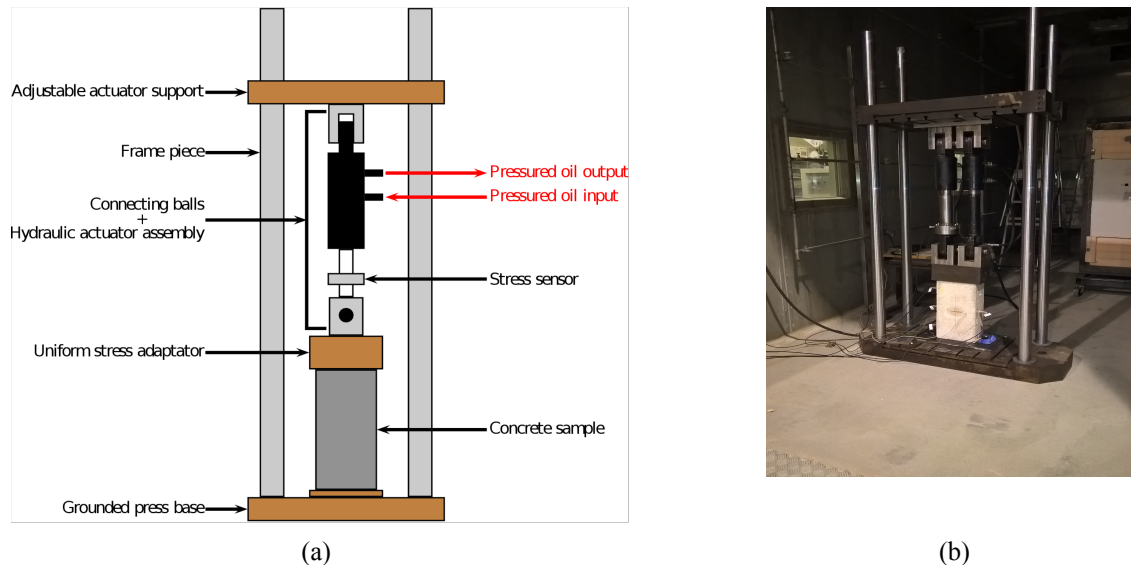


FIGURE 3. Experimental set-up for static loading of 0,5 m x 0,25 m x 0,12 m concrete slabs (a) schematic drawing (b) picture.

In Fig. 4a the surface wave phase velocity corresponding to a wavelength equal to 0,03 m is plotted as a function of the applied force. First we can notice that the two measurements on face B are superimposed showing the reproducibility of the experimental set-up but also the robustness of the surface wave measurement protocol consisting in averaging 50 random positions of MACSYS probe seismograms. Similar precision, at low stress level, has been observed before in the literature [5] but with lower frequencies and with sensors glued on the concrete that are not removed from the concrete during all the tests. With our protocol and the dry coupling transducers, the

surface wave phase velocity is measured with a precision better than ± 5 m/s. Unsuccessful experimental attempts to reach similar precision in surface wave velocity measurement with air coupled devices are also reported [6].

In this experiment an increase of 10 MPa corresponds to an increase of around 5 % of the surface wave phase velocity. The measurements on face A shows similar trend although not strictly superimposed to the result on face B certainly due to the non perfect parallelepipedic shape of the concrete slab.

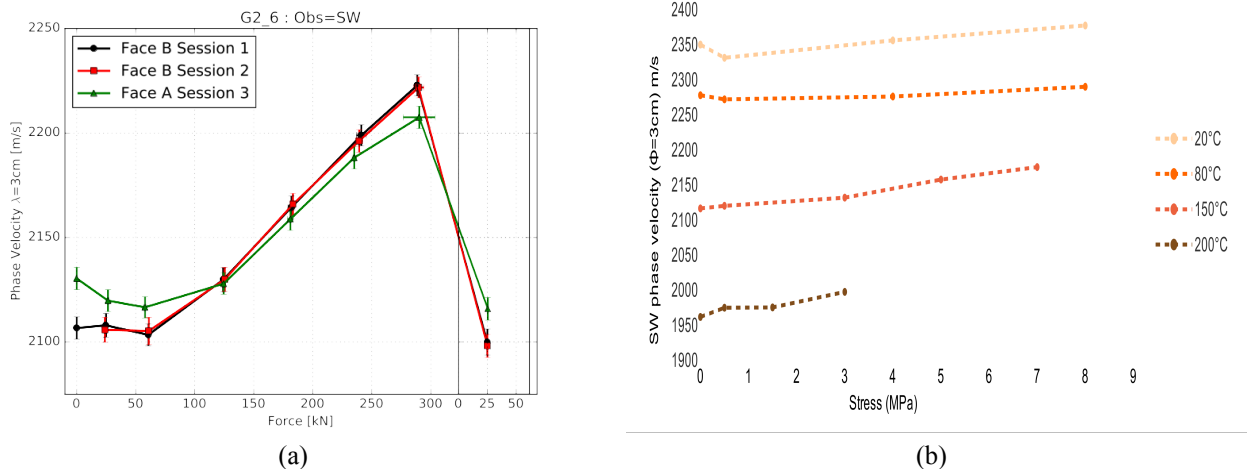


FIGURE 4. Surface wave phase velocity for a wavelength equal to 0,03 m as a function of applied compression stress (a) on a concrete slab that has been thermally damaged at a temperature equal to 150°C while under compression, (b) comparison of measurements on 3 slabs damaged at 3 temperatures 80°C, 150°C and 200°C (no loading during damage) and one sound slab (20°C).

Second experiment

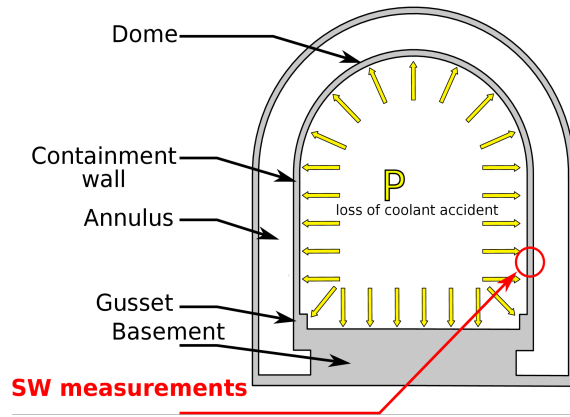
The same surface wave measurement protocol has been followed on three concrete slabs that have been thermally damaged at 80°C, 150°C and 200°C (without any loading during the damaging process) and on one sound slab.

The results are presented in Fig. 4b. First it can be noticed that thermal damage is clearly visible with velocities ranging from 2350 m/s for the sound slab down to 1950 m/s for the slab thermally damaged at the highest temperature (200°C). Second, whatever the compression load applied (here below 8MPa), the surface wave phase velocities remain clearly distinguishable between the damage levels. The sensitivity of surface wave is thus sufficient to quantify thermal damage even if the concrete is under compression.

In absence of thermal damage for this concrete mix the surface wave phase velocity increases of 2,5% when the stress increase from 0 MPa to 10 MPa.

EXPERIMENTS AT VERCORS MOCK-UP

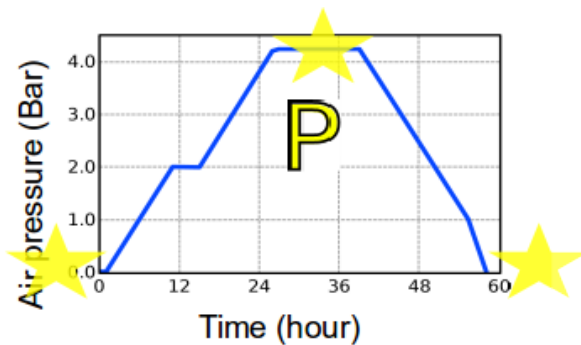
Figure 5 shows a picture the VeRCoRS mock-up where MACSYS probe has been used to monitor the stress increase during a simulated decennial test. The later consists in increasing the inner pressure to a nominal 5 bars value to map cracks and to quantify leakage. Access to the inner wall (Fig. 5b) was granted by EDF for measurements before pressurization, at the maximum pressure level (before water aspersion) and then back to the no pressure state (Fig. 6a). The time allocated for surface wave measurement is less than 20 minutes so that only two points are measured. The two points are located near to each other and in the lower part of the mock-up, near the gusset. Figure 6b shows that the increase of inner pressure corresponds, at its maximum, to a decrease of 1 % of the surface wave velocity. A decrease is indeed expected, as before pressurization the concrete is under compression due to the pre-stressing, and compression is reduced when the inner pressure increases. We have seen in the lab that a decrease of 1 % correspond to a variation of the stress level for the sound concrete of around 5 MPa. This order of grandeur is feasible here as our surface wave measurements are performed near the gusset which is not the area in the containment wall where the compression is the more reduced during the test.



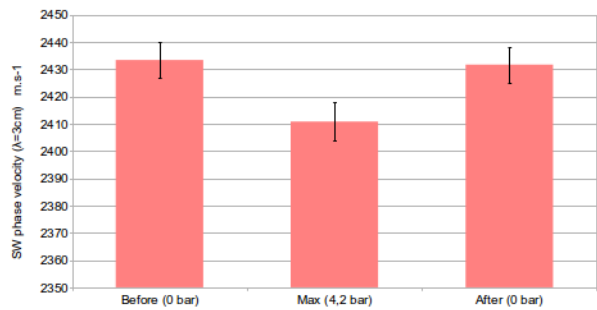
(a)

(b)

FIGURE 5. (a) Picture of the VerCoRs mock-up. (b) Schematic view with the location of the surface wave measurement circled in red.



(a)



(b)

FIGURE 6. (a) Inside pressure during the test, the yellow stars indicate when it was possible to enter the structure to make surface wave measurements. (b) Measured surface wave velocity before, during and after pressure increase on a specific point.

CONCLUSION

In this paper we have shown that the surface wave probe MACSYS together with a measurement protocol based on the summation of 50 seismograms over concrete material disorder makes it possible to have a phase velocity precision better than 5 m/s. This precision is needed if stress variation less than 10 MPa are monitored. The probe was used first on a series of lab test and then on the EDF VerCoRs mock-up.

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