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Construction and quality control of a 100 m deep diaphragm wall

La construction et le contrôle de qualité d'une paroi moulée de 100 m de profondeur

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SYNOPSIS: To check the feasibility and the quality of a very deep diaphragm wall, a field trial was performed. A 100 m deep diaphragm wall formed of 3 panels has been constructed in the Milan sandy gravelly soil by means of a hydraulically driven milling machine with reverse circulation of mud. The results of the monitoring carried out in order to evaluate the reliability of the different instrumentation systems for the definition of the panel geometry and the quality of both joints and concrete are described.

1. FOREWORD

It is well known that the depth limit of diaphragm walls excavated with grab equipment ranges between 40 and 50 meters. Beyond these depths and with such kind of equipment, the deviation of the wall from the vertical that can be expected (normally between 0.5 and 2% depending on the soil type) offers poor guaranty on the quality of the joints and therefore on the continuity of the diaphragm.

In spite of this, the need for very deep diaphragms (up to 100 m depth) is growing especially in the field of the hydraulic cut-off walls. Among the excavation equipment that allows to maintain high quality levels in terms of verticality and joint contact there are those that use percussion tools with direct or, most commonly, reverse mud circulation (De Paoli 1984), but their production rate is very low. In the last decade a new kind of equipment has been developed. The slurry trench cutter basically consists of a heavy steel frame mounting two milling wheels on horizontal axes, propelled by hydraulic motors. The cutter continuously loosens and reduces the size of the soil material, mixing it with a bentonitic suspension. The debris are then removed by reverse mud circulation.

This type of equipment was firstly developed in France (Solétanche Hydrofraise) (Fenoux 1982) and, some years after, in Germany (Bauer City Cutter) and in Italy (Rodio Romill).

At the end of 1987, Rodio Company, assisted by the S.G.I. (Studio Geotecnico Italiano), has financed and run a field test to verify the feasibility and the quality of a very deep unreinforced concrete diaphragm constructed with a Romill equipment. The test consisted in digging and casting three panels to a depth of 100 m from surface: the joints were obtained by grinding the concrete of the primary panels to form a planned overlap of 0.15 m (fig. 1a). The Romill, 3.15 m long and 0.80 m wide, was fitted with a directional drilling control system to correct its driving direction while digging (fig. 2). It was also equipped with electronic sensors to collect and record on real time the operating parameters such as depth, instantaneous vertical rate of excavation, pressure exerted on the soil, power output of the hydraulic motors and rotational velocity of the two milling wheels. Considering the depth that had to be reached, an extended monitoring program was planned to control and check the geometry of each single panel and the position of each panel relative to the other two. The controls were carried out during construction so as to be able to steer the Romill. The results of these controls were checked after completion

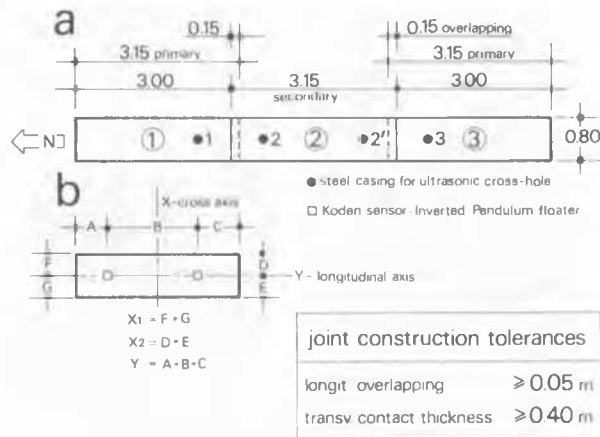


Figure 1. a) Plan view of test panels. b) Arrangement of Kodan sensors and Inverted Pendulum floaters.

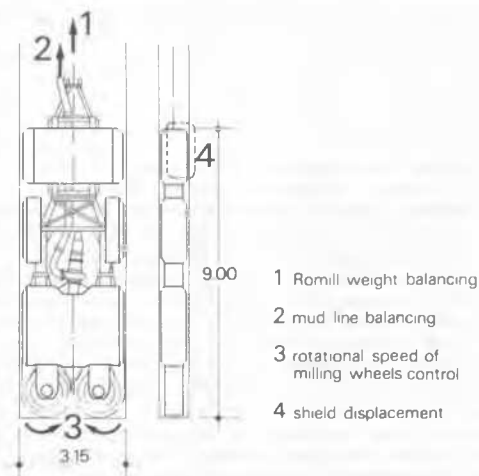


Figure 2. Scheme of Romill directional drilling control system.

of the excavation. The quality of concrete and joints were tested with non destructive ultrasonic methods. The results obtained have given an idea of the fairly wide field of application as well as of the performance limitations and potentials of the various monitoring procedures. In fact, it is interesting to point out that, with the joint construction tolerances reported in fig. 1, the maximum differential displacement among contiguous panels at a depth of 100 m had to be less than 0.4 m and 0.1 m in the transversal and in the longitudinal planes respectively: this gives an idea of the complexity of the subject in question.

2. SOIL CONDITION

The field test was run in the south-eastern outskirts of Milan. The subsoil of Milan is mainly composed of recent alluvium with variable mixtures and alternations of gravel, sand and silt (fig. 3a). The relative density varies from fair to very high, increasing with depth (fig. 3b). In the field test area the water table is located at 4 m below ground level.

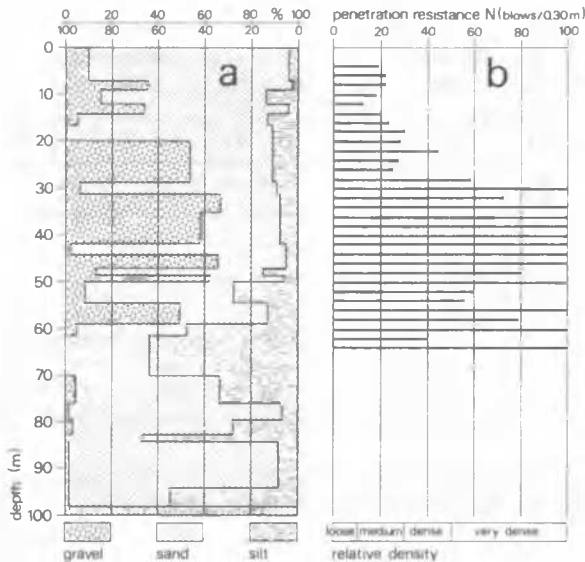


Figure 3. Grain size (a) and SPT (b) profiles of trial field soil.

3. INSTRUMENTATION

The following instrumentation was used:

- KODEN Ultrasonic Echometer (Koden 1984)

This instrument permits measurement of both three-dimensional location and actual sizes of the excavation: a cable suspended probe is vertically lowered into the trench; it continuously emits ultrasonic waves that rebound off the excavation walls. The waves are then received back by the sensors, which transmit the return time to the recording station. The recorder produces a graph showing the distance between the excavation walls perpendicular to the ultrasonic signal and the probe vertical line of descent. In the field, each panel was tested along two verticals of descent to enable the evaluation of the complete geometry through six distance measurements according to the scheme of fig. 1.

- EASTMAN Gyroscopic Inclinometer (Eastman 1986)

This instrument was used only to measure the angle of azimuthal rotation; such measurements were then combined

with those of verticality obtained by ICARO Biaxial Inclinometer.

- Inverted Pendulum System

This instrument consists of two floaters (fig. 1b) each of them connected to a 1.6 mm diameter metal wire. These wires, passing through a couple of pulleys attached to the Romill head, are operated from the surface by two winches. Readings with this instrument can be taken once the excavation is completed by lowering the Romill frame again into the excavation and stopping it at predetermined depth intervals.

- ICARO Inclinometric System

This system consists of two monoaxial inclinometers mounted on the Romill frame and lying in the longitudinal and the transversal planes respectively. The two inclinometers are connected to a read-out unit placed in the operator's cabin. The unit allows to view the data as they are being recorded. It is therefore possible to detect any deviation from the vertical and steer the Romill to correct its direction during the digging process. This feature of the system constitutes an important development with respect to the previous ones widely used also on grab equipment (Tornaghi 1985), which allowed to check the panel geometry only after completion of the excavation.

4. CHRONOLOGICAL DEVELOPMENT OF THE MONITORING PROCEDURES

In the original monitoring plan it was foreseen to run a continuous control of the verticality of the panel, based on the ICARO system combined with periodic EASTMAN readings of the azimuth, in order to determine the tri-dimensional orientation of each panel and steer the milling machine accordingly. At the end of the drilling, the KODEN echometer readings should have given a confirmation on the previous results together with the actual dimensions of the excavation. Knowing the tridimensional location and the dimensions of each panel it should have been possible to geometrically calculate the expected overlap of the contiguous panels.

Having followed the above procedure, the excavation of the first panel drilled (no. 1) resulted practically vertical, according to the ICARO indications. On the other hand, considerable discrepancies were noticed when the results of the ICARO and KODEN readings were compared (fig. 4). It was then clear that another measuring system was needed based on a different physical principle in order to have a reference for all the measurements. It was so decided to use the Inverted Pendulum system during the construction of the remaining panels.

Also the excavation of the second panel, the number 3, was steered following the ICARO-EASTMAN indications: KODEN and Inverted Pendulum measurements resulted congruent, while ICARO readings were remarkably divergent from the other two (fig. 5).

For the excavation of panel no. 2, the last one, the following decisions were then taken:

a) The ICARO system was not going to be used as the guiding instrument to steer the Romill. Fine tuning of the instrument was necessary, with particular attention to its zeroing, to some software aspects and to the influence on the readings of the tool vibrations during trenching.

b) The KODEN readings were going to be intensified to verify its reliability and repeatability as a function of the mud quality, the sensor used and the distance between excavation wall and sensor.

The experience gained during the execution of this panel showed an appreciable congruity between KODEN and Inverted Pendulum readings (fig. 6) but their discrepancy from ICARO results, recorded during excavation, was also confirmed. Vice versa a good correlation between the three types of measures was found using the ICARO System as a bidirectional inclinometric probe upon completion of the excavation.

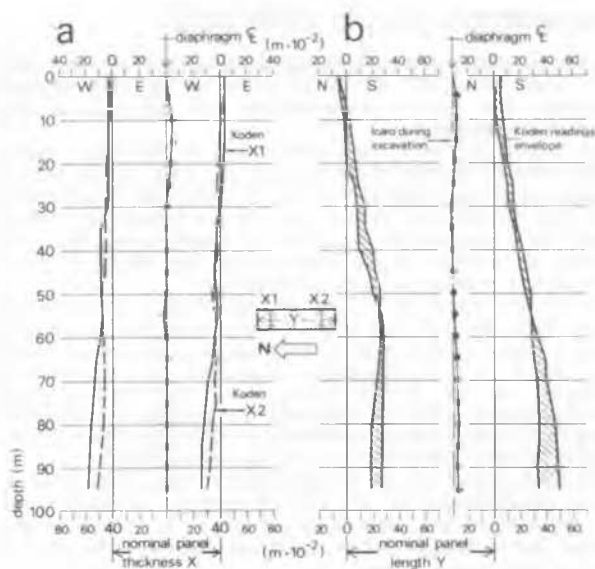


Figure 4. Deviation from the vertical of panel no. 1 on cross (a) and longitudinal (b) planes according to different measurement systems.

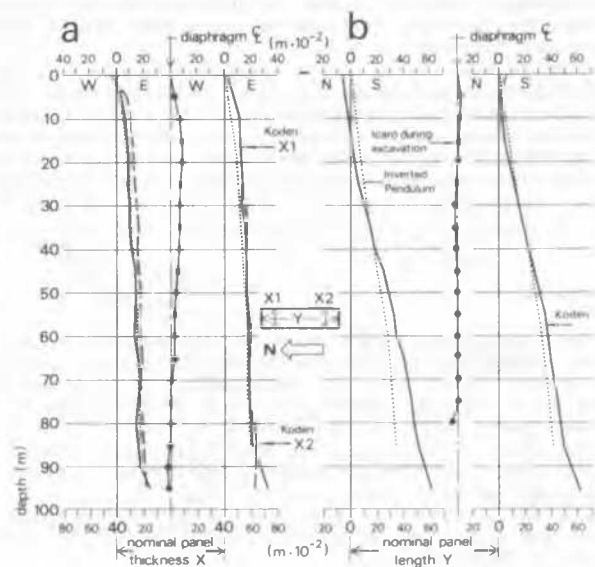


Figure 5. Deviation from the vertical of panel no. 3 on cross (a) and longitudinal (b) planes according to different measurement systems.

5. GEOMETRY DATA ANALYSIS

a) The absolute deviation from the vertical in all of the panels was in the ranges 0.10 to 0.20/100 along the transversal plane and 0.25 to 0.60/100 along the longitudinal plane while the torsion was negligible.

b) The longitudinal deviations, the only ones that could affect the expected continuity between the panels, were all in the same southward direction. This reduced substantially the differential displacements among adjacent panels. It is difficult to establish whether the absolute deviations were due to the fact that panels 1 and 3 were guided by the ICARO-EASTMAN system, which

eventually resulted unreliable, or whether the deviations were due to an objective tendency of the Romill to deviate. In the latter case it is impossible to evaluate whether the parallelism is accidental or not. In any case during the excavation of panel number 2 the Romill showed no difficulties in following the concrete sides of the two primary panels already poured.

c) All the KODEN readings, the only ones available for every panel, were combined as shown in figures 7a and 7b to evaluate the geometry of the joints between panels. These data confirmed the existence of a perfect contact between panels in the transversal direction; however some doubts remained about the overlap in the longitudinal direction in the joint between panels 2 and 3. The most pessimistic combination of the readings indicated that there could be a window at a depth between 45 and 75 m, whereas any other combination of data excluded this possibility.

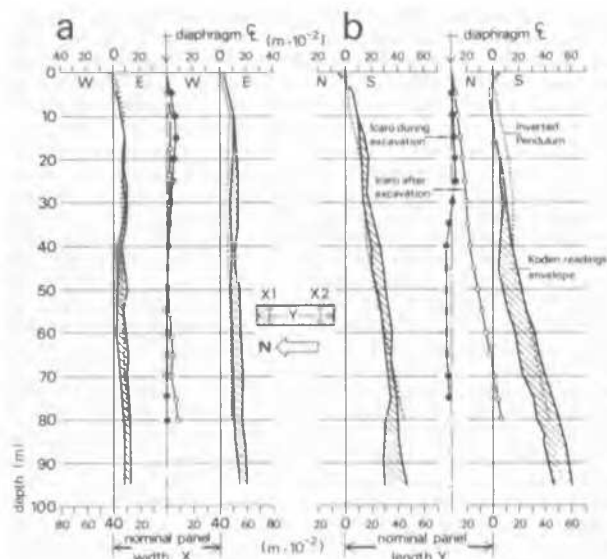


Figure 6. Deviation from the vertical of panel no. 2 on cross (a) and longitudinal (b) planes according to different measurement systems.

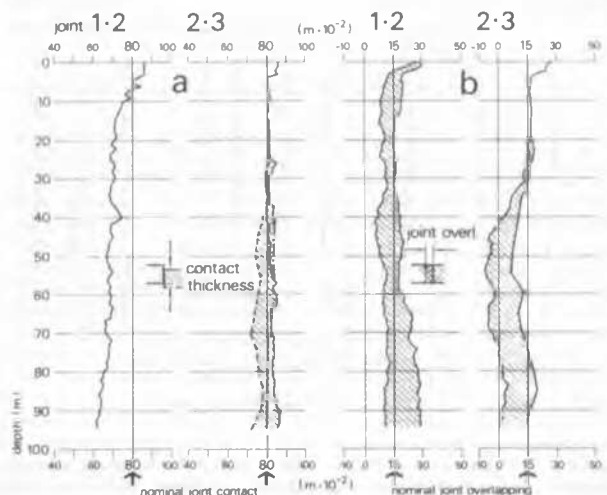


Figure 7. Contact thickness (a) and overlapping (b) of joints 1-2 and 2-3 resulting from Kodex readings envelope.

6. QUALITY CONTROL OF CONCRETE AND JOINT CONTINUITY

Four steel pipes were embedded in the panels to a depth of 96 meters to perform ultrasonic Cross-Hole tests, as shown in fig. 1a. The graphical outputs of these tests are represented by the so called "variable density graphs" where the time elapsed between signal emission and reception as well as the waves properties (amplitude, frequency and form) are recorded versus depth.

The check (Ismes 1988), based on the analysis of both the return time (fig. 8a) and the representation of received signals, did not reveal any transmission anomaly that could be related to the presence of defects in the concrete or that could indicate a lack of continuity among the three panels. This eliminated the doubts on the continuity of the joints, that were left by the most unfavourable KODEN results. However, consistent variations in the return time along the depth were recorded and attributed to a lack of parallelism between the pipes because no sudden drop of signal occurred at any depth. In particular it was probable that the pipe 2' moved away from pipe 3 and towards number 2. This supposition was confirmed by the Eastman gyroclinometric measurements of deviation (fig. 8b) which permitted a more realistic evaluation of the actual distance between the pipes as a function of the depth. Based on these calculated distances, diagrams representing the waves propagation velocity, which is linked to the elasticity properties of the concrete, were obtained (fig. 8c). However, also in this occasion, a problem of measurement accuracy became prominent in the deepest portion of the panels where the distance between pipes number 2 and 2' at a depth of 95 meters was measured to be only 0.95 m. In such contest an error of 0.1 m, for example, in the measured distance causes an error of 16% in the evaluation of the velocity. However in order to notice a 0.10 m variation in the distance at a depth of 95 m, it is necessary to have an instrument able to measure inclination angles with a precision of 3/100 of a degree, even having disregarded the azimuthal deviation. As a consequence, in the authors' opinion, any consideration on the elastic characteristics of the concrete at great depths (beyond 70 meters) should be considered unreliable due to the insufficient accuracy of any realistically achievable deviation measurements.

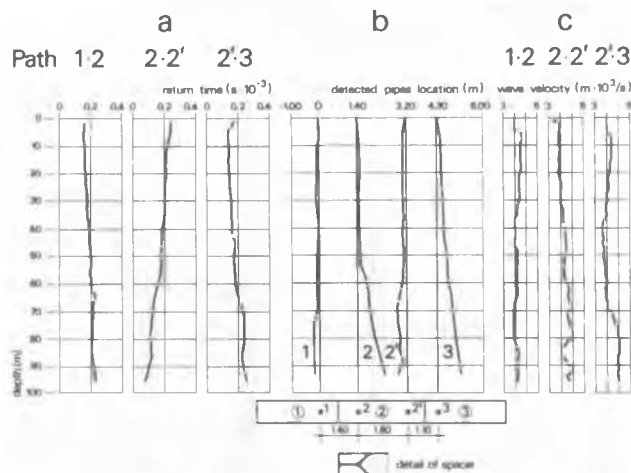


Figure 8. Cross-hole tests. Time elapsed between signal emission and reception (a), pipes location detected on longitudinal axis (b) and waves propagation velocity (c).

7. CONCLUSIONS

The field test showed the feasibility of a diaphragm wall to a depth of a 100 meters in an alluvial soil without boulders. The Romill demonstrated its ability to dig practically vertically.

The deviations were more pronounced in the longitudinal direction than in the transversal one. This should not be a surprise since any difference in rotational speed between the two milling wheels results in tangential forces along the longitudinal axis. As a consequence, the usefulness of monitoring and controlling the speed of rotation of the wheels has been pointed out.

Since the steering system of the Romill gave encouraging results, the availability of an on-line system to monitor vertical deviation during excavation seemed helpful. Due to the difficulties connected with an on-line azimuthal reading, it is believed that such system could also be based only on biaxial inclinometric measures. Owing to these considerations, a further development program of the ICARO system has been undertaken.

The experience gained in subsequent works demonstrated heavy interference of the Romill digging vibrations on the inclinometer instantaneous readings. This problem was solved by reducing the tolerances between the Romill shields and trench sizes.

For the certification needs at the end of the excavation, both the KODEN Echometer and the ICARO System gave acceptable results when compared with the present state of the art. But the repeatability and the accuracy of both systems did not always appear optimal at great depths. The Inverted Pendulum has been very useful for periodical controls.

The Cross-Hole System, since some time largely used to check the deep foundation concrete quality, showed its efficiency in checking also the continuity of the joints. On the contrary, considerations on the elastic properties of the concrete can be drawn from this kind of tests only provided that the measuring pipes are installed as parallel as possible since monitoring of their deviation with the required accuracy is practically impossible.

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