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Monitoring and quality control of a 100 metre deep diaphragm wall

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To check the feasibility and the quality of a very deep diaphragm wall, a tern of adjacent panels has been constructed, up to a depth of 100 m, 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 panel geometry and the quality of both joints and concrete are described.

The use of instrumentation based on different physical principles allowed the cross checking of measurements as well as the evaluation of the accuracy and sensitivity of each single procedure to be performed. The trial field was successfully carried out and the feasibility of a diaphragm wall of such a depth was demonstrated and corroborated by a reasonable level of quality control.

1. BACKGROUND

It is generally found that when excavating diaphragm walls through soils with conventional grabs the maximum practical depth is 40-50 m. The amount of panel deviation from the vertical may be 0.5 to 2% depending on the ground conditions, and below such depths, the quality of the panel joints may be unacceptably low. The continuity and effectiveness of the whole diaphragm will therefore be compromised.

Conventional grabs are also severely limited in their ability to excavate bedrock, when, for example it is required for hydraulic or structural reasons to toe the wall more than a nominal distance into the bedrock. In such cases, the traditional method is "chiselling" - the dropping of a large and heavy sharp edged tool to fracture the rock for subsequent grabbing. This is usually a tedious and frustrating process of limited depth potential.

There are other inherent problems with conventional diaphragm walling, which are attended to with varying degrees of success on different sites. These include production rate, over break and irregularity of panels (especially in the upper reaches), the presence of large, hard boulders and the handling and disposal of debris and bentonite slurry.

Some alternative technologies have been developed on an ad hoc basis to guarantee diaphragm quality in terms of verticality and joint contact, in particular geological conditions (De Paoli, 1984). These have featured large diameter percussive tools with direct, or more commonly, reverse mud circulation. All these variations have, however, shown a common drawback, namely very low production rates.

Despite these operational drawbacks, world demand for diaphragm walling has continued apace with prime applications being for support of deep excavations in urban areas, (Bruce, 1988) and for hydraulic cut offs for dams and other water retaining structures. Walls of the order of 100 m in depth are being specified, often through difficult or mixed geologies, and always to very strict construction specifications.

A typical case, albeit to shallower depths, is the recent repair of Fontenelle Dam, in Wyoming (Figure 1). Constructed in the early 1960's, this 1600 m long clay core embankment dam rises a maximum of 34 m above the local bedrock - inter-bedded medium hard horizontal sediments. Despite early rock grouting efforts, monitoring showed that there was a strong possibility of cata-

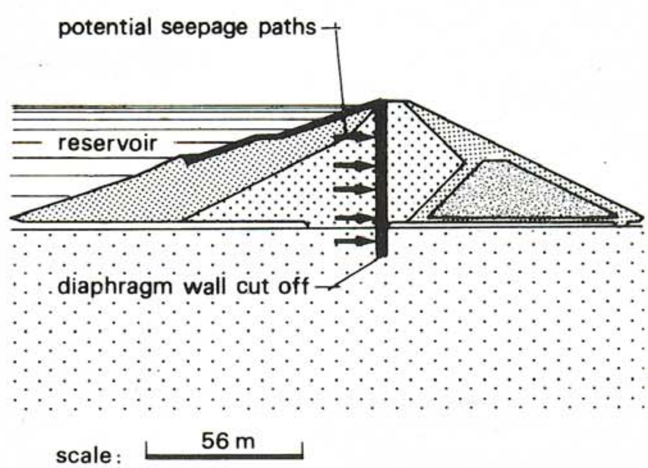


Fig. 1 Cross section of Fontenelle Dam Wy - USA

strophic failure as a result of water piping through, and under, the contact zone. The major element in its repair was a concrete diaphragm wall, in panels a minimum of 0.8 m wide, to be installed from the dam crest, through the embankment and for an average of 14 m into the bedrock. The Government specified a minimum thickness of wall, between adjacent panels, of 0.45 m.
Given the seriousness of the situation, the work also had to be carried out in a very restricted time interval.

This task, and numerous others equally as challenging (eg Anon, 1988), have been undertaken around the world in the last few years by a new and different concept of diaphragm wall excavation. The machine (Figure 2) consists basically of a heavy steel frame on which are mounted two large contrarotating milling wheels. These are powred by hydraulic motors. The whole machine is lowered progressively into the trench and excavates and crushes the soil or rock. These debris are simultaneously mixed with the bentonite slurry and removed to the surface by a large reverse circulation mud pump located just above the cutting wheels. Cleaned and fresh bentonite slurry is fed back into the top of the trench to maintain the slurry level and so trench stability. This approach to excavation equipment was developed firstly in France and is referred to by Solétanche as the Hydrofraise. (Fenoux, 1982). Later versions have been produced by Bauer in Germany (City Cutter) and by Rodio in Italy (Romill).

2. THE ROMILL TRIAL

In view of these increasingly onerous demands being placed on a new technique, Rodio recently financed and ran a full scale field test, in collaboration with the Studio Geotecnico Italiano. Its prime aims were to verify the constructional feasibility of a 100 m deep unreinforced concrete wall and to demonstrate the quality to be anticipated. In addition, it permitted the effectiveness and relative accuracy of different types of instrumentation to be judged.

2.1. Soil Conditions

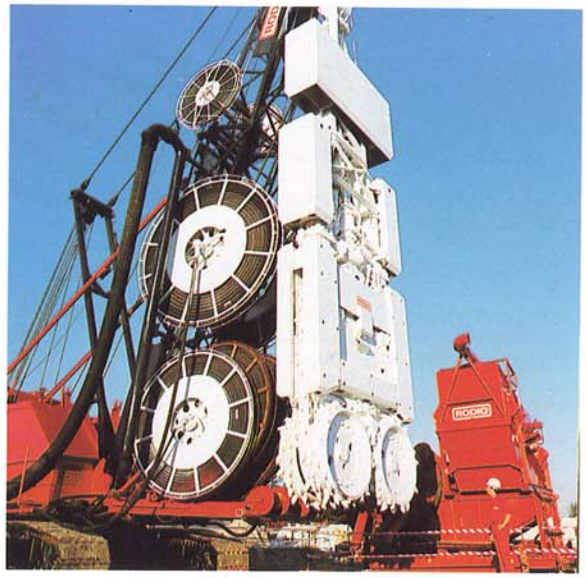
The test site was located in the south-eastern outskirts of Milan. The soil is principally recent alluvium comprising variable combinations and interbeds of gravel, sand and silt (Figure 3a). The relative density ranges from moderate to very high, generally increasing with depth (Figure 3b). At the test site the water table is 4 m below the surface.

2.2. Test Layout

The test was to excavate and concrete three contiguous panels to a depth of 100 m, as shown in Figure 4a. Construction of the Primary Panels (1 and 3) was to be followed by the Secondary Panel 2, nominally incised about 0.15 m into the flanking Primaries, reflecting typical industry standards, minimum joint overlaps of 0.05 m (longitudinal) and 0.40 m (transverse) were selected (Figure 4a). It may be noted that the panel joints are not planar. Due to the geometry of the cutting wheels, an irregular interface is provided, which is advantageous in promoting physical interlocking of the adjacent panels.

2.3. Romill Excavator

As shown in Figure 2, the Romil used for the trial was 3.15 m long and 0,80 m wide. It was equipped with electronic sensors to collect and record via a data acquisition system the major operational parameters in real time.



Romill milling machine

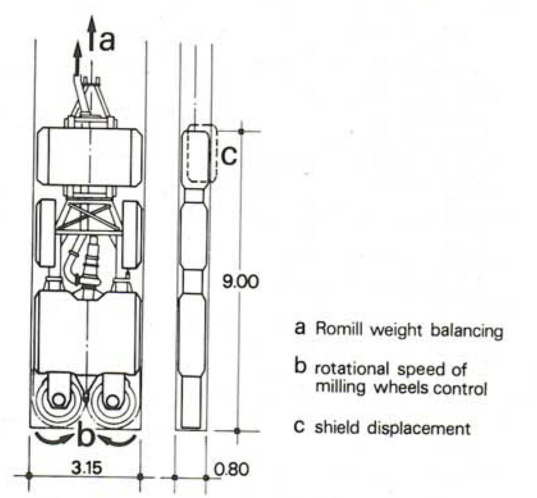


Fig. 2 Drawing of Romill, showing the directional drilling capabilities

These parameters were:

- excavation depth, and rate of excavation (eg Figure 5)
- rotational speed and torque of each milling wheel
- flow and pressure of mud pump hydraulic system
- vertical thrust exerted on the soil by the Romill.

The data acquisition system was designed to make a complete reading cycle approximately thirty times per minute, and it displayed on the monitor the arithmetic mean of each parameter every ten cycles. It transferred to store the readings every 0.10 m of excavation progress.

The Romill itself featured several means of steering it in the course of excavation, in response to the positional data referred to the operator by the instrumentation described below. As shown in Figure 2, these facilities were:
A) variation of the thrust: it has been found that the effective weight of the Romill influences the excavation direction. For example in soft or loose soil, overthrust may induce a punching effect and sudden deviations, whereas in compact soil, or rock, almost all the weight of the Romill must be used to enhance the ripping action of the teeth of the milling wheels. B) variation of the relative rotational speed of the milling wheels: this obviously varies the inclination of the whole machine in the longitudinal plane. C) extending the upper frame shield: acting like a hydraulic jack, this shield acts on the excavation walls, and forces the Romill to change direction in the transverse sense.

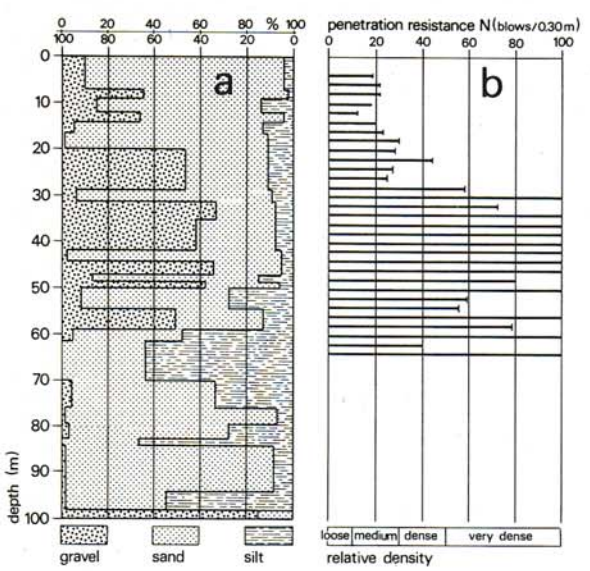


Fig. 3 a) Grain size and b) SPT value profiles at the test site

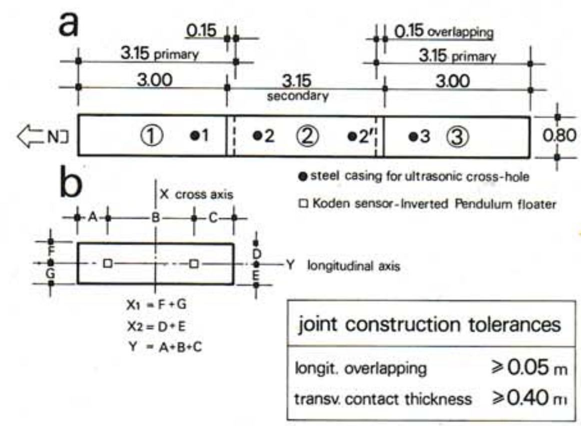


Fig. 4 a) Plan view of test panels b) Arrangement of Koden sensors and Inverted Pendulum floaters

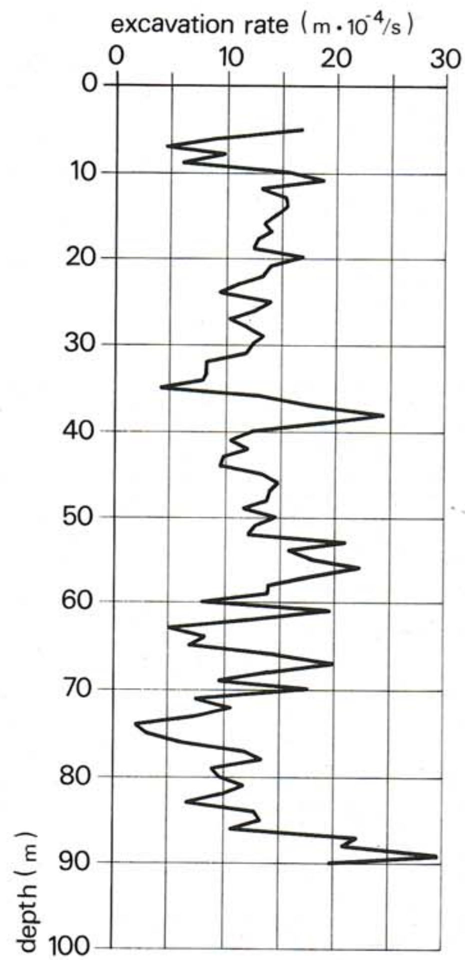


Fig. 5 Typical log of excavation rate with depth. (Panel 2)

2.4. Monitoring Programme

An intensive monitoring programme was planned to verify the geometry of each panel, and the position of each panel relative to the other two. These checks were carried out during construction so that the Romill could be guided accordingly. The results of this exercise were in turn to be checked independently after excavation. Finally non destructive ultrasonic methods were planned to judge the nature of the concrete and the joints. This testing schedule was able not only to monitor the performance of the Romill, but also to compare the relative potential and limitations of the various monitoring methods.

3. DETAILS OF THE INSTRUMENTATION

3.1. ICARO Inclinometer System (Figure 6)

Two monoaxial inclinometers were mounted on the Romill frame, one in the longitudinal plane, (Y), and one in the transverse plane (X). Both were connected to a readout unit placed in the operator's cabin. Data could be viewed in real time and so it was possible to detect immediately any deviation from the vertical and steer the Romill accordingly, during excavation. This feature of the Romill system represents a significant development with regard to earlier systems used on grabs, (Tornaghi, 1985). These permitted checking of panel geometry only after the completion of the excavation.

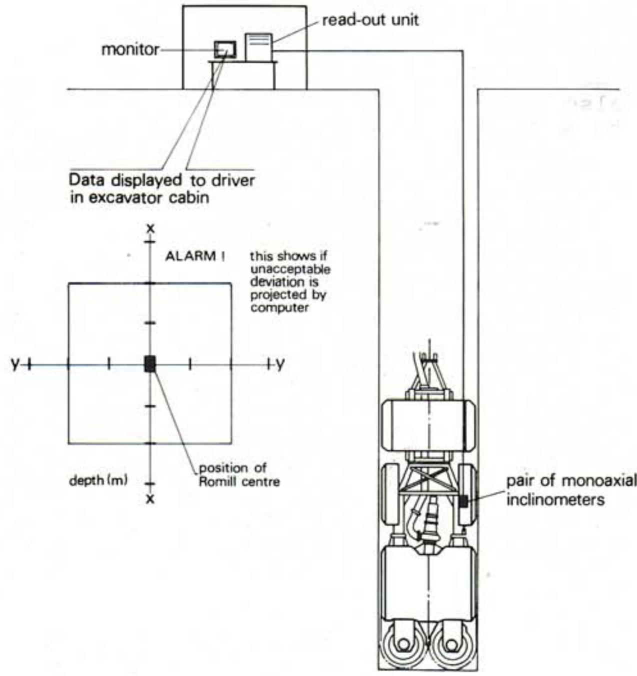
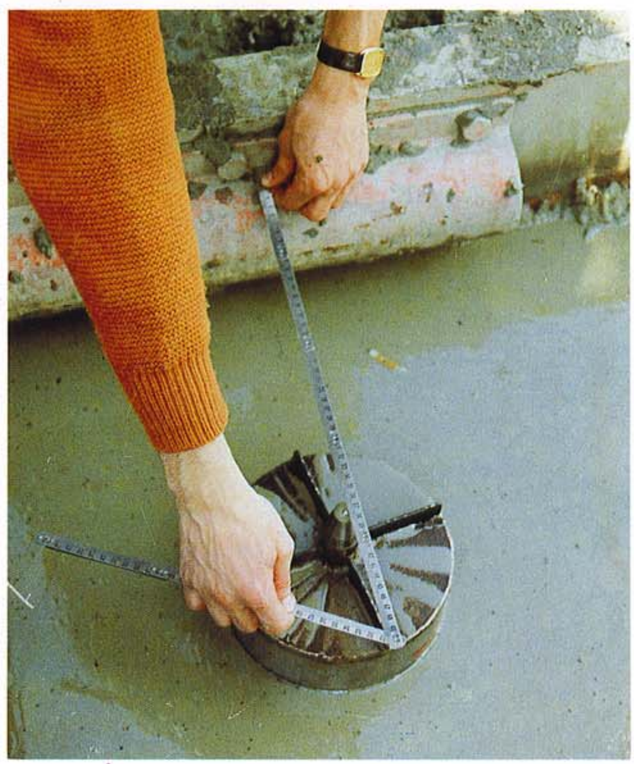


Fig. 6 ICARO inclinometer system

3.2. Eastman Gyroscopic Inclinometer

This instrument (Eastman, 1986) was used only to measure the angle of azimuthal rotation. These measurements were then combined with those of verticality obtained by the ICARO system.

ICARO inclinometer system. Data displayed to driver in the excavation cabin.



Inverted pendulum floater during measuring.

3.3. Inverted Pendulum (Figure 7)

The instrument consists of two floaters, also shown in Figure 4b, each connected to a 1.6 mm dia. steel wire. These wires passed through a pair of pulleys on the Romill head and were attached to winches at the surface, bearing on a reference frame. Readings could be taken, once excavation was complete, by lowering the Romill to predetermined depths in the excavation.

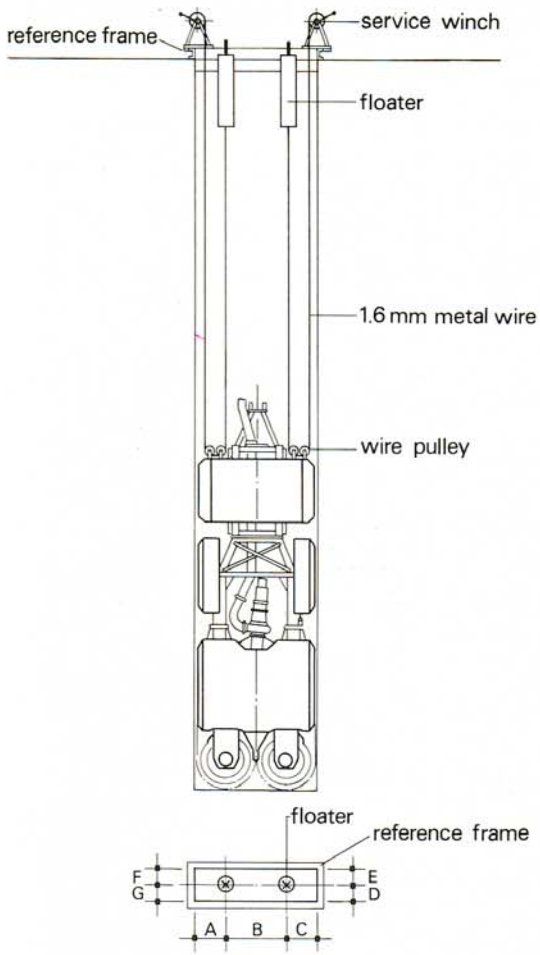


Fig. 7 Inverted pendulum system

3.4. Koden Ultrasonic Echometer

With this instrument (Koden 1984), both the three dimensional orientations, and the actual dimensions of a panel can be continuously checked. A cable suspended ultrasonic probe is lowered into the trench, continuously emitting waves in orthogonal directions which are reflected off the walls. The return waves are received by the probe sensors which transmit the return time to the surface recording station. As the wave velocity is known, distance can be calculated, and a chart is produced showing the distance between the probe and the walls, with depth.

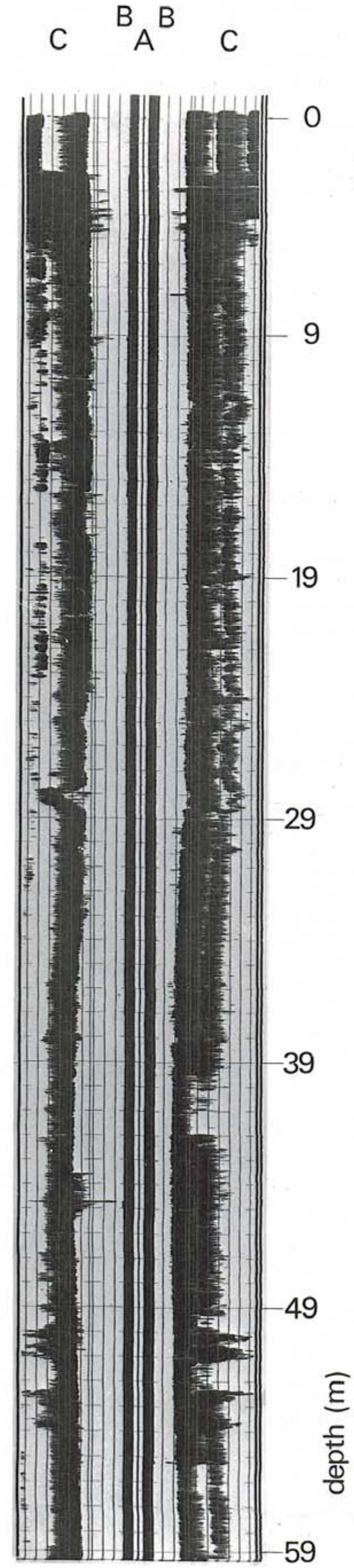


Fig. 8 Typical KODEN log. (60 m deep test panel)

The radius of operation of the probe can be 1 to 4 m, with an accuracy of +0.2% full scale. The best results are obtained when the mud is clean and the unit weight about 1.06 kg/dm^3.
However it is also practical at values up to 1.20 kg/dm^3 and with poor sand content.
In this trial each panel was tested down two lines (Figure 4b) to permit evaluation of the complete geometry through six distance measurements.

By way of example, Figure 8 shows a typical log for a 60 m deep section of panel. The vertical line (A), bordered by two dark strips (B), represents the vertical descent path of the probe. The trench wall profile is shown by the inner borders of the dark strips (C). From such a log, horizontal excavation sections (Figures 9 and 10) can be drawn, as well as the vertical sections illustrated below. These latter permit panel overlapping and joint contact to be established.

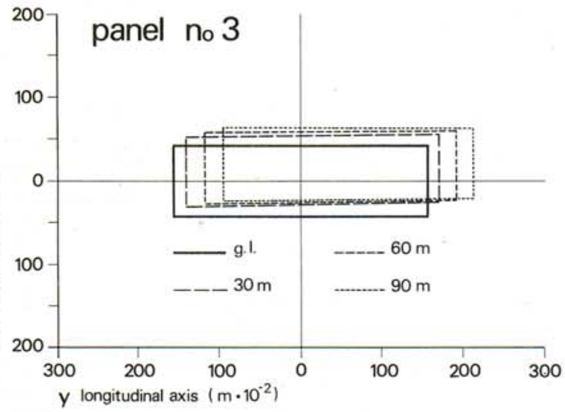


Fig. 9 Horizontal sections of one panel at various depths, using KODEN data

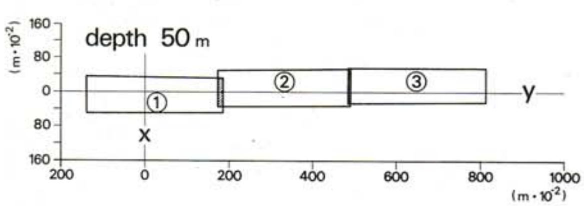


Fig. 10 Horizontal sections of three panels at same depths, using KODEN data

4. CHRONOLOGICAL DEVELOPMENT OF THE MONITORING PROCEDURES

It was originally foreseen that a combination of continuous ICARO, and periodic EASTMAN, readings would determine satisfactorily the three dimensional orientation of each panel, and the need for any direction correction of the Romill. Koden data, at the end of excavation, were then expected to confirm these orientations, and provide actual panel dimensions. Nominal panel overlaps could then be calculated.

However, a problem was found on the first panel (No. 1). Whereas the ICARO measurements indicated almost perfect verticality, the KODEN data showed otherwise (Figure 11). Another measuring system was therefore sought, operating on a different principle, and the Inverted Pendulum was selected for use in the remaining panels.

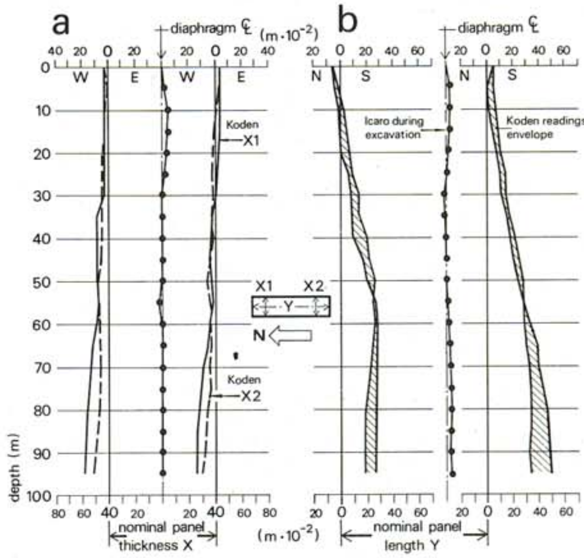


Fig. 11 Deviation from the vertical of panel 1 on (a) transverse, and (b) longitudinal planes as measured by different systems

The second panel (No. 3) was then excavated using the ICARO-EASTMAN combination. Again a discrepancy was found with the KODEN readings, which this time were confirmed by the Inverted Pendulum method. (Figure 12).

In this light, the following decisions were made prior to the excavation of the third panel (no. 2):

- the ICARO system was not to be used as the basis for steering the Romill. Adjustments were necessary, especially with respect to its zeroing, some software aspects, and to its sensitivity to vibrations during excavation
- the frequency of the KODEN readings were to be intensified to verify its reliability and repeatability as a function of mud quality, the sensor used, and the distance from trench wall to sensor.

During the subsequent construction of panel 2, close correlation between KODEN and Pendulum was again clear (Figure 13), as were their differences to the ICARO data. However a good correspondence between the three sources of data was found when the ICARO was used simply as a bi-directional inclinometric probe, after excavation of the panel.

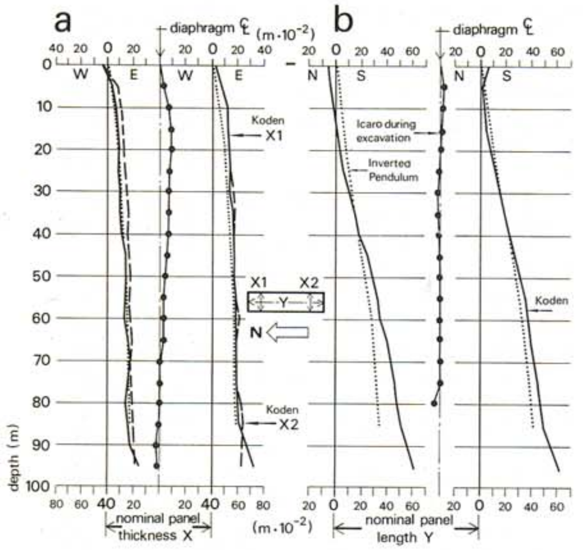


Fig. 12 Deviation from the vertical of panel 3 on (a) transverse, and (b) longitudinal planes, as measured by different systems. Note the congruence of KODEN and Pendulum readings

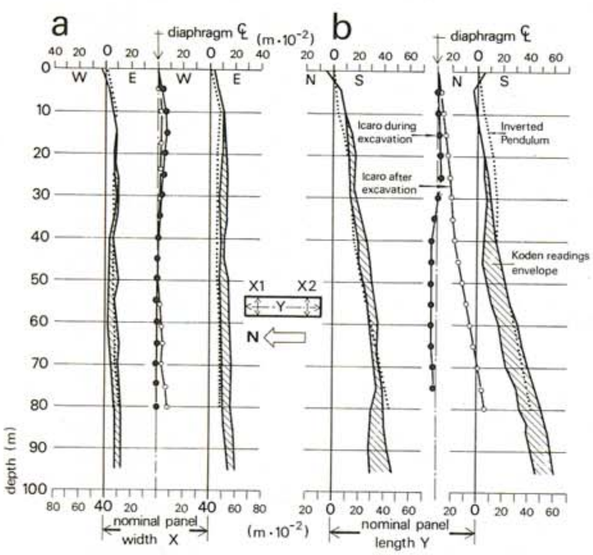


Fig. 13 Deviation from the vertical of panel 2 on (a) transverse, and (b) longitudinal planes, according to different measurement systems.

The concrete in the primary panels was well in excess of 15 N/mm^2 at the time of the Secondary excavation.

Upon completion of the three major panels to 100 m depth, a fourth panel was excavated nearby to a depth of 60 m to check the modified ICARO and its interaction with the Romill directional excavation capabilities described above. As shown in Figure 14, excavation proceeded vertically to 30 m depth at which point the shield (Figure 2) was activated. From 30 to 34 m the shield was moved westwards thus initiating a displacement of the Romill off vertical. From 36 to 47 m the shield was moved eastwards to reduce the rate of deviation. This was accomplished around 44 m. At 49 m the shield was restored to centre, but the effect of the previous movement was still real, progressively forcing the Romill back to the vertical axis.

After withdrawal of the Romill, KODEN was used (Figure 8) to check the excavation geometry. These data confirmed the information provided in real time by the modified ICARO.

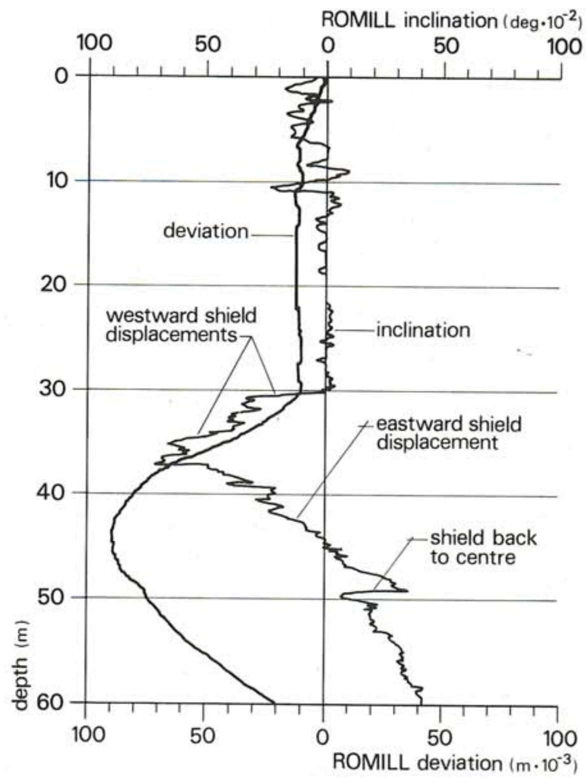
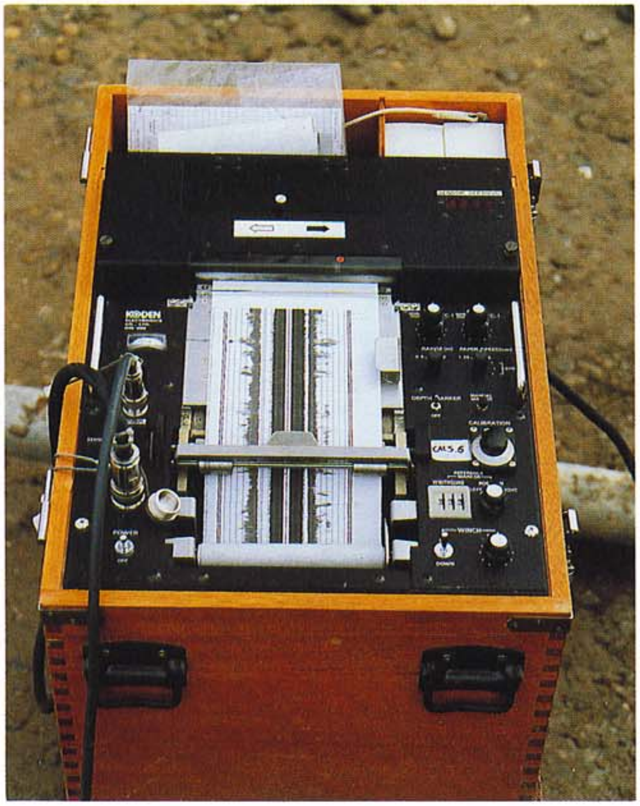


Fig. 14 Comparison of Romill shield displacements and subsequent Romill deviation during directional excavation test. The KODEN log of same panel is shown in fig. 8



KODEN ultrasonic echometer.

5. REVIEW OF DATA ON TRENCH GEOMETRIES

Major points to emerge from the intensive instrumentation were as follows:

1. The absolute deviation from the vertical in all of the panels was in the ranges 0.1 to 0.2% along the transverse axis, and 0.25 to 0.60% in the longitudinal axis. Torsion was negligible.
2. The longitudinal deviations were all in the same southerly direction. This therefore reduced substantially the differential displacements between 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 questionable ICARO-EASTMAN system, or whether they were due to some inherent tendency of the Romill itself to deviate in this fashion. In any case, the Romill had no problem in following the concrete sides of the two primary panels when the time came to excavate the intermediate Secondary panel.
3. All the KODEN readings, the best data available for all panels, were combined as shown in Figure 15, to assess the geometry of the joints between panels. Perfect contact between panels in the transverse direction was confirmed. However, some doubts were cast on the longitudinal overlap between Panels 2 and 3. Using the most pessimistic combination of readings, at the most unfavourable ends of their envelopes, a "window" from 45 to 75 m could be inferred. However, this interpretation was not confirmed by any abnormality in the Romill excavation parameters record between such depths and the likelihood of a window actually existing was regarded as remote.

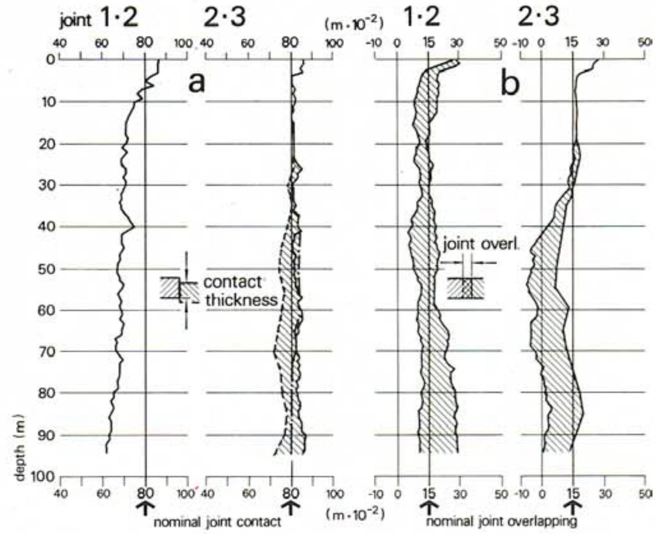


Fig. 15 a) Contact thickness, and b) overlapping of joints between panels 1-2 and 2-3, based on envelope of KODEN data

6. CONCRETE AND JOINT CONTINUITY QUALITY ASSURANCE

Four steel pipes were embedded to a depth of 96 m in the panels, as shown in Figure 16, to permit ultrasonic cross hole testing. The nature of the testing is illustrated in Figure 17. The graphical outputs of such tests are represented by "variable density graphs" where the time elapsed between signal emission and reception, as well as the wave parameters themselves, are recorded with depth.

The testing was run independently by Ismes (1988). Based on the analysis of all the data no transmission anomaly could be detected, which could otherwise be ascribed to defects in the concrete, or discontinuities between the panels. This survey therefore eliminated the possibility of the "window", raised by the most pessimistic review of the KODEN data.

However, consistent variations in the signal return time with depth were noted. These were attributed to imperfect parallelism between the measuring pipes since no sudden variation in signal was found. For example it was calculated that

Pipe 2' (Figure 16) had moved away from pipe 3 and towards Pipe 2. This was precisely confirmed by EASTMAN gyro-inclinometric measurements.

Using these revised distances, diagrams showing the wave propagation velocity were prepared (Figure 16 c). Even so, a problem of measurement accuracy became obvious in the deepest portion of the panels where the distance between Pipes 2 and 2' at a depth of 95 m was measured to be only 0.95 m. Here an error of 0.1 m, for example, in the measured distance causes an error of 16% in the evaluation of the velocity and so of the apparent concrete quality.

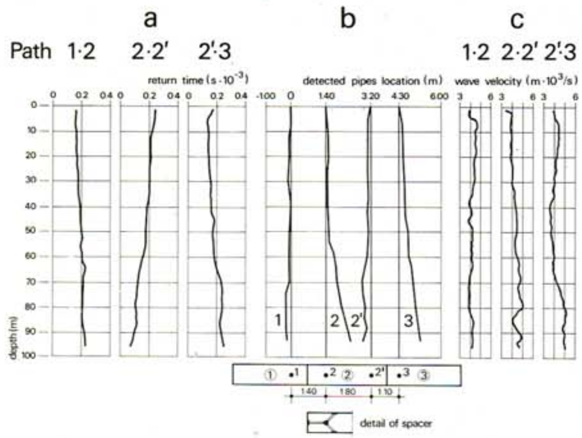


Fig. 16 Cross-hole tests (a). Time elapsed between signal emission and reception (b), pipes' location detected on longitudinal axis and (c) wave propagation velocity

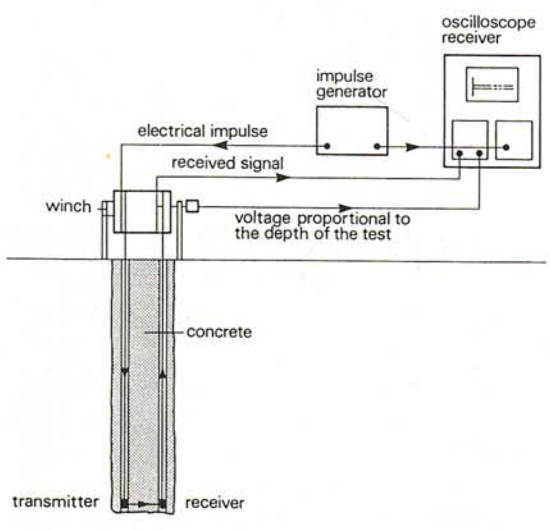
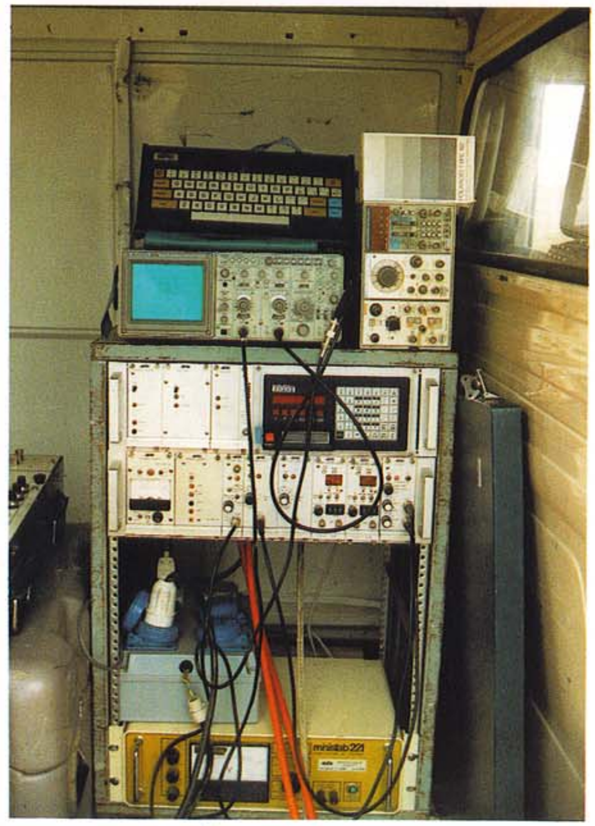


Fig. 17 Operating principle of cross-hole ultrasonic testing



Monitoring unit for cross-hole ultrasonic testing

However in order to define a 0.10 m variation at a depth of 95 m, one must have an instrument able to measure inclination angles to a precision of 0.03 degree, even having disregarded the azimuthal deviation.

The authors therefore conclude that any such investigation of the elastic characteristics of the concrete at depths beyond, say, 70 m, should be regarded as impractical, due to the restrictions placed by deviation measuring instrumentation.

7. CONCLUSIONS

The field trial proved the feasibility of constructing high quality diaphragm wall panels to a depth of 100 m in the prevailing mixed alluvial conditions. The Romill demonstrated its ability to excavate in an almost perfectly vertical fashion.

The deviations measured were within the targeted tolerance, being more pronounced in the longitudinal sense than in the transverse sense. This is scarcely surprising as any difference in rotational speed between the milling wheels results in tangential forces along the longitudinal axis. This confirms the usefulness of monitoring and controlling the rotational speed of these wheels during excavation.

The measurements of panel geometry and attitude after excavation confirmed that the KODEN and Inverted Pendulum methods proved more reliable and accurate than the original ICARO-EASTMAN combination.

However, the latter pairing was modified, and testing in the separate, successful directional excavation trial to 60 m confirmed its improvement to KODEN standards. It must be noted, however, that even the KODEN system has reduced repeatability and accuracy at the greater depths.

The Cross Hole ultrasonic testing proved its effectiveness in checking joint continuity, and removed the last doubt about a potential "window" at depth between Panels 2 and 3. However, accurate conclusions as to the elastic properties of the concrete at depth can only be drawn with this method if the measuring pipes are installed as parallel as possible, as the establishment of their deviation to the necessary degree of accuracy is practically impossible with current instrumentation.

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