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Bi-layer diaphragm walls: Experimental and numerical structural analysis

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ABSTRACT

The bi-layer diaphragm wall, a new type of wall, consists of two concrete layers, the first of which is poured and the second sprayed, in different construction stages. A major aim of the research conducted is to maximize the functional attributes of the second layer, enhancing both structural performance and watertightness. The central objective of this study is to corroborate the structural behaviour of these walls in experimental and numerical terms. It follows a three-step methodology: a full-scale experimental campaign; development of a Finite Element Model (FEM) capable of predicting the structural behaviour of the wall; and, assessment of the second layer contribution. The experimental campaign confirmed the viability of the constructive solution and the FEM model accurately reflected the experimental data. A comparison between the bi-layer wall and other single-layer walls showed that the contribution of the second layer permitted reductions in first-layer reinforcement, adding to its various other functional advantages.

1. Introduction

Large cities are encouraged to make efficient use of space, especially below ground level [1]. Expanding fleets of vehicles require the adaptation of their transport systems for circulation and parking. Urban metro systems and road tunnels help to reduce traffic congestion and to minimize contamination. The excavation works that these structures require should not adversely affect existing infrastructure and should minimize any interruption to the daily life of the city. In this scenario, the *conventional diaphragm wall* technique frequently represents a viable solution.

Economies in a diaphragm wall project may be achieved at the beginning of the design process, when selecting the method, the construction sequence, and the type of wall, and in the optimization of the temporal and permanent use of the retaining structure [2]. Accordingly, material consumption, the final dimensions of the wall, maintenance requirements, and construction complexity should all be evaluated before the adoption of any one solution [2].

A widespread problem associated with this construction technique is leakage whenever the walls are erected in water-bearing ground. As there are no existing techniques to make diaphragm walls fully watertight, a variety of alternatives have been developed to cope with the leakage problem [3].

A common technique is repairing locally with a waterproof mortar render over areas where leakage is detected. However, leakage usually only appears over long time periods, at different times, and in different areas of a wall, causing problems for both owners and contractors. A less widely applied solution consists of casting a second layer of waterproof mortar (or concrete) over the inner face of the walls. Since the whole surface is covered, this is an effective albeit expensive solution [4]. Finally, another common practice, already standardized in British construction codes [5,6], is to construct an inner wall separated by a cavity [3], at the bottom of which the water is left to accumulate before it is pumped out. Although dry inner walls are still constructed, this solution presents some drawbacks: the inner wall loses significant volume in view of the cavity and construction tolerances and it may, at worst, conceal dangerous leakages and even structural problems.

The major aim of this research project is to maximize the functional attributes of the second layer of concrete, based on the second lining solution described above, by allowing it to play a structural role, in addition to its initial intended purpose (waterproofing). In accordance with the structural role of the second layer, the thickness and reinforcement of the first layer may therefore be reduced. The dimensions of this bi-layer diaphragm wall and its improved watertightness suggest that it could be a feasible structural solution.

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Thus, the *bi-layer diaphragm wall* represents a new type of slurry wall made of two bonded concrete layers poured and then sprayed, in separate stages. The first is a conventional reinforced concrete (RC) diaphragm wall. Once this wall attains the necessary strength, soil within the perimeter is excavated and removed, and the second layer, this time of sprayed concrete with steel fibres (SFRC) and a waterproof admixture, is applied.

This research work has been structured into four main areas: (a) Structural level analysis; (b) sectional level analysis; (c) bonding between layers; and (d) general design and optimization. The main objective of this paper is to corroborate the structural level behaviour of the bi-layer diaphragm walls both experimentally and numerically (i.e., the first of the aforementioned areas). To do so, a methodology with three components was followed: (a) demonstrate the viability of the proposed solution, by reporting on the experimental campaign to assess the structural behaviour of the bi-layer walls; (b) develop a Finite Element Model (FEM) capable of predicting the structural behaviour of the bi-layer diaphragm walls; and (c) assess the structural contribution of the second layer with the cast RC wall through a theoretical example of use.

2. Experimental program

2.1. General information

The structural behaviour of various bi-layer walls at a building site in Barcelona (Spain) was analyzed in a full-scale experimental campaign. Before construction began, a geotechnical study analyzed the characteristics of the soil. Inclinometer tubes were placed inside the walls to analyze the structural behaviour of the composite element, and test specimens with poured concrete were used for material characterization, as described below. The bond between layers, transversal displacements and anchorage loads were also measured and have been reported previously elsewhere [7–9].

Fig. 1a shows the layout of the building site. Standard construction methods were used to build the diaphragm walls that enclose the building site around its perimeter. The figure also shows the location of the two experimental walls, both running parallel to the street. Within the walls, the two instrumented panels are labelled Wall W35 and Wall W45. The number indicates the width of the first layer of cast concrete (e.g. 35 cm). Cross-sections views of these panels are shown in Fig. 1b including the finished frameworks up to street level (level: 0.00 m), the temporary anchors, and the phreatic level. The cross-section detail of a finished bi-layer wall is schematically represented in Fig. 1c.

The design of the experimental campaign was based on an uncoupled structure-section analysis. The structural analysis was performed using the Cypecad [10] module for diaphragm walls: a FEM-based program which considers soil-structure interaction, modelling the walls with FEM beam elements and the soil with a Winkler model. The numerical simulation of the mechanical behaviour of the composite sections of the Wall was performed with the model "Analysis of Evolutionary Sections" (AES) [11,12]. This model allows simulation of the non-linear response of sections built with different materials (concrete and steel) and the structural contribution of the SFRC under tensile stress.

The Auxiliary Anchorage in Wall W35 was deliberately placed to cause flexural moments in the wall once the bi-layer section had been constructed, facilitating the analysis of the structural collaboration. When the Auxiliary Anchorage was eliminated, a bending increase in the wall occurred to redistribute the forces to the remaining anchorages and to the footing of the wall, placing the bi-layer cross-sections under greater bending moments.

2.2. Construction of experimental bi-layer walls

Details of the bottom-up construction sequence of the experimental bi-layer walls are summarized in Table 1. The following information is given for each stage: a brief description; number of days from panel casting to completion of the stage; a reference name used to identify the inclinometer reading; and the structural scheme of the model. A schematic diagram of the different construction sequence can be seen in Fig. 2. Details of the materials used and of the construction sequence are given below.

A conventional reinforced-concrete diaphragm wall constituted the first layer of the bi-layer walls, with a theoretical compressive strength at 28 days of $f_c = 30$ MPa [13].

The excavation process began immediately after the cap beam had been placed in position over each complete line of panels. The main characteristics of the anchorages are given in Table 2. The rods were positioned when the excavation reached the required depth. Panels with anchorages alternated alongside panels with no anchorages. Struts instead of anchorages were fixed to the corner panels. A single line of anchorages was used around the entire perimeter, except in the experimental panel of Wall W35, where two anchorages were used.

Following completion of the excavation, surface preparation and roughening took place to improve the bond. Wall W45 was prepared by milling and Wall W35 by milling plus the addition of an epoxy bond product before spraying.

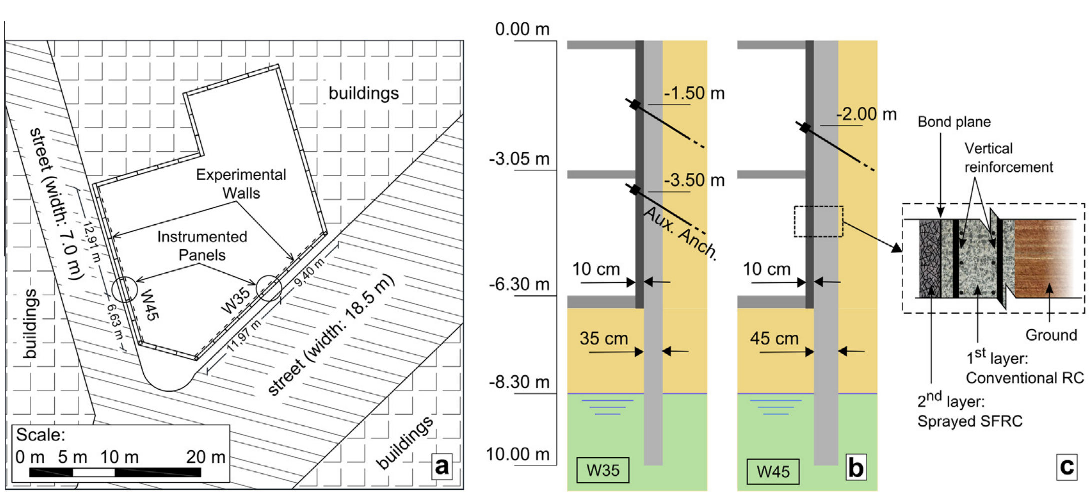

Fig. 1. Experimental building: (a) site plan; (b) general cross-section; (c) detail of bi-layer cross-section.