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Bi-layer diaphragm walls: Parametric study of construction processes

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ABSTRACT

The bi-layer diaphragm wall is a new type of slurry wall, designed to improve watertightness and to counter leakage problems. These walls consist of two bonded concrete layers: the first, a conventional Reinforced Concrete (RC) diaphragm wall and the second, a sprayed Steel Fibre Reinforced Concrete (SFRC) layer with a waterproof additive. Here, we analyse and quantify the influence of different construction process parameters on the effectiveness of the bi-layer diaphragm wall technique. Thirty numeric simulations were conducted with an uncoupled structure-section analysis, placing special emphasis on the SFRC layer contribution. The results show that, in all cases, the main flexural strength is provided by the RC layer, with a secondary flexural contribution (between 8% and 15%) by the sprayed SFRC layer. Using satisfactory spraying sequences (detailed herein), a reduction in the steel reinforcement of the RC layer can be obtained in every structural configuration and construction sequence, reaching a maximum percentage reduction of 7.0% of the total bending reinforcement. The displacements are almost completely governed by the thickness of the first layer, and a minor reduction (less than 7.3%) is obtained, when the second layer is included.

1. Introduction

Diaphragm walls are hardly ever fully watertight, as there is generally a degree of permeability between their panel joints [1]. Hence, some techniques have been developed to deal with the leakage problem in diaphragm walls built in water-bearing ground [2]. The bi-layer diaphragm wall [3] is a new type of slurry wall, mainly designed to counter leakage. The waterproofing system, added in the course of internal site excavations, assumes a structural function as an integral part of the wall structure.

A generic solution and part of the construction of the first experimental walls of this type [3] can be seen in Fig. 1. These walls consist of two bonded concrete layers poured and then sprayed, in separate stages. The first is a conventional Reinforced Concrete (RC) diaphragm wall (which forms the simple cross-section, see Fig. 1c). Once this wall attains the necessary strength, subsoil in contact with the wall within the perimeter is excavated and removed, and the second layer, this time of sprayed Steel Fibre Reinforced Concrete (SFRC) and a waterproof additive, is applied (both layers form the compound cross-section, see Fig. 1b).

The main *objective* of this paper is to analyze and quantify the influence of different construction process parameters in the efficiency of the bi-layer diaphragm wall technique, measured in terms of reduction in the reinforcement and in displacement. This paper is part of an experimental and theoretical study of bi-layer diaphragm walls, structured into four main areas: (a) structural level analysis [3,4]; (b) sectional level analysis [4]; (c) bonding between layers [5]; and (d) general design and optimization. This paper sets out the basis for the fourth of these aforementioned areas.

The parameters under study are grouped into two categories: (a) specific bi-layer diaphragm walls characteristics (i.e. number of spraying stages, depth of sprayed concrete layer); and (b) general diaphragm walls and construction characteristics (i.e. wall thickness, construction sequence, final structural geometry).

Many studies have reported on the parametric analysis of deep excavations, studying the parameters of the second of the aforementioned categories. The studies mainly involve two approaches: analysis of a comprehensive case history database (e.g. [6–9]), and numerical analysis based on models calibrated against well documented case studies (e.g. [10–13]). The main focus of these studies is on wall and ground movements, due to their importance in the prediction of damage to adjacent buildings.

Thirty numeric simulations of diaphragm walls, with varied parameters, were run with an uncoupled structure-section analysis to fulfill the objective. Besides the displacements, the structural response was also analyzed, focusing on the bending moments, with special emphasis on the SFRC layer contribution.

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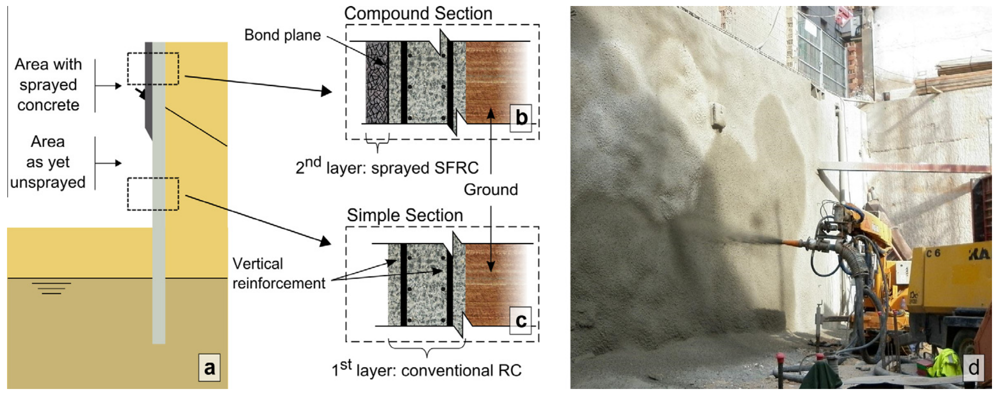

Fig. 1. Bi-layer diaphragm walls: (a) general scheme; (b) compound cross-section; (c) simple cross-section; and (d) spraying of an experimental wall.

2. Methodology

2.1. Model description

A 2D Finite Element Model (FEM) developed in PLAXIS was used in the structural study. The soil was modelled with the Hardening Soil model (HS) [14] and the wall and supports with linear elastic elements. In the FEM model, the stiffnesses were updated from the simple cross-section to the compound cross-section in the corresponding wall sections that had been sprayed after each of the spraying stages. No movements were considered during struts and slabs installation, and the walls were considered "*wished in place*", i.e. the stress changes or displacement of the wall installation in the soil are not considered in the model [11].

In all cases, diaphragm walls of 20 m in height were built for subsequent excavation work to a depth of 12.5 m, and with embedded footings of 7.5 m in depth. No adjacent buildings were considered (i.e. no external loads were introduced in the models). A sandy soil ("*Lake sand layer*") and its parameters were taken from a case presented elsewhere [15]. This is a good quality, only slightly deformable soil. The type and characteristics of the finite elements, the mesh discretization and its boundary conditions, as well as properties taken for the wall, anchorages, and slabs, are the same as those in [4]. The struts were modelled with *fixed-end anchors*. A normal stiffness of EA = $2.00 \cdot 10^4$ kN/m/m for the superior strut and of EA = $4.00 \cdot 10^4$ kN/m/m for the inferior one was selected, both with an equivalent support length of 10 m (with stiffnesses in the range of the Kung [10] parametric analysis).

The "Analysis of Evolutionary Sections" (AES) model was used to perform the numerical simulation of the mechanical behaviour of the composite cross-sections of the wall [16,17]. It simulates the non-linear response of cross-sections built with different materials (concrete and steel) and, most especially, the structural contribution of the SFRC under tension. The characteristics of the aforementioned structural and sectional models are fully described in [4], likewise, the properties of the materials were also taken from the aforementioned paper.

The design of the reinforcement followed the same criteria in all cases: (a) a symmetric reinforcement at each face of the wall with the minimum reinforcement area ($A_{s,min}$) [18]; and (b) extra reinforcements ($A_{s,ext}$) in each point where the design bending moment (M_d) exceeded the ultimate bending moments (M_u) given by the reinforcement of (a). Only tensioned bars were taken into account in the calculation.

For the sake of simplicity, the reinforcement was defined indicating only the necessary steel area, without defining the type, diameter, and number of bars. On the other hand, although the criteria used in the analysis are not completely realistic (for example, in some cases, reinforcement is placed just to cover a small increase in the bending moments), they allow quantification and comparison of the quantity of reinforcement steel required in the different solutions.

Table 1
Parameters and alternatives for each case.

Parameter	Alternatives	Description
Number of layers (NL)	ML	Mono-layer
	BL	Bi-layer
1st layer thickness (W1)	55	55 cm 1st layer
	60	60 cm 1st layer
2nd layer thickness (W2)	0	Mono-layer type
	10	10 cm 2nd layer
Construction sequence (CS)	BUs	Bottom-Up with struts
	BUa	Bottom-Up with anchorages
	TD	Top-Down
Final number of underground levels (NU)	2u	Infrastructures
	4u	Dwelling basements
Number of spraying stages (NS)	0S	Mono-layer type
	1S	1 stage spraying
	2S	2 stage spraying
	4S	4 stage praying
Depth of sprayed concrete layer in the last stage (DS)	M	Mono-layer type
	A	Depth: −12.5 m
	B	Depth: −11.5 m
	C	Depth: −10.5 m

2.2. Parameters under study

Table 1 presents the parameters and a brief description of the alternatives that are studied. As the combination of all alternatives would lead to a total of 120 cases, a selection of combinations (30 cases) is presented, in order to analyse the influence of: type of wall (mono-layer or bi-layer), construction sequence, number of underground levels in the final configuration, number of spraying stages and depth of sprayed concrete layer.

Given the large number of cases, the following labels are proposed for ease of identification:

NL/W1 – W2/CS/NU/NS/DS

where NL is the number of layers of the wall: conventional diaphragm walls, referred to as mono-layer walls (ML) for the sake of clarity, and bi-layer walls (BL). W1 is the thickness, in cm, of the 1st layer (the conventional RC wall): 55 and 60. W2 is the thickness, in cm, of the 2nd layer (the SFRC sprayed layer): 0 (ML wall)