



Large diameter shafts for underground infrastructure



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ABSTRACT

The technique of large diameter shafts for deep excavations was analysed in terms of its basic construction elements, reported literature cases and design methods. The effects of the construction sequence and the geological deposition on the behaviour of the shaft was analysed using 3D finite element models. Induced stresses and displacements on the soil mass were investigated. Three methods to assess the stability of the shaft lining were presented and employed as a post-processing stage of analysis of the models. The results indicated a major influence of the height of the vertical excavation stages on the shaft behaviour, markedly on the induced settlements. The lining analysis also demonstrated the effects of the vertical excavation stages and how different safety assessment methods can produce significantly different results.

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1. Introduction

Urban population growth and the consequent need for transportation required a rapid increase in underground infrastructure over the last decade. However, the demand considerably exceeds the present use of the underground space. Mass transportation systems generally face difficulties to operate on the surface when the urban population exceeds one million people. According to the 2009 UN census there were more than 350 cities worldwide with such a population. It is evident that several of these cities lack the economic conditions to engage in underground construction projects, however, the pressing demand that is now evident in cities like Sao Paulo, Singapore and Hong Kong will certainly spread through other major cities worldwide.

Subway systems and road tunnels make it possible to reach the city centres within reasonable time without affecting the densely constructed city centres. To access these underground facilities it is necessary to connect the underground structure to some points of interest in the surface. These accesses can be ventilation systems, emergency exits or subway stations. Stations are massive spaces for facilities such as stairs, elevators, selling points, security installations and for passengers in transit. It is essential that these stations be located within a reasonable distance from the main points of transportation demand, which tend to be in the most populated areas of the city.

Subway stations are built through a deep trench or bench excavation. The slope created on the bench excavation (Fig. 1) can reduce the need for stabilizing structural elements and simplify the access of construction equipment. After the station structure is built the pit is refilled up to the surface level. However, bench slopes increase the volume of transported material and the surface area disrupted by the construction. This last point is frequently a limiting factor for urban constructions, especially in city centres where these stations are normally located. Therefore vertical excavations are normally the choice for the construction of underground stations.

There are several types of retaining structures for deep excavations (Fernandes, 2010), but underground stations are traditionally built with retaining walls. Standard constructions employ diaphragm walls, excavated by clam shell using bentonite as a support fluid. Alternative techniques, that do not require a support fluid, are the cutter soil mixing (CSM) walls and the piled walls (Fig. 2a). The piles can be placed along intersecting or spaced sections depending on the soil stability.

The construction of plane cantilever walls is normally not feasible considering the depth of these excavations, and therefore anchors or struts are generally used. The regulations in some cities restrict the use of permanent anchors (Fig. 2b) beyond the perimeter of the station grounds, because they interfere with the underground space of other lots. On the other hand, struts (Fig. 2c) severely impair the movement of construction equipment and the transportation of wastes in and out of the excavation pit in comparison with the free internal space provided by anchored walls.

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Fig. 1. Deep bench excavation.

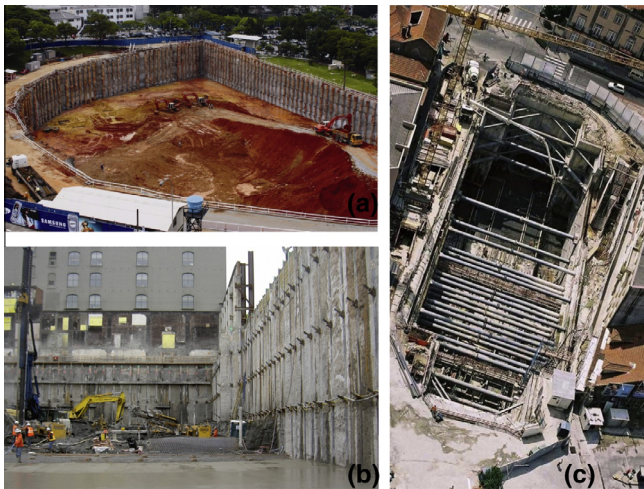


Fig. 2. Vertical excavations: piled wall (a); Anchored wall (b) and strutted wall (c).

Circular diaphragm walls are self-stable structures because the circular geometry creates a stable ring under compression. Case histories have shown that this solution normally resulted in smaller settlements than rectangular excavations (Muramatsu and Abe, 1996). Recent reports of a 46 m diameter shaft for an underground car park in Nantes, France (Marten and Bourgeois, 2005) and a 15.7 m diameter shaft for TBM extraction in Rome, Italy (Furlani et al., 2011) show that these structures are still in use with considerable diameter. Fiala et al. (2011) performed a parametrical numerical analysis of shafts with different shapes, stiffness, construction sequence and embedded length and reported what circular shafts resulted in a lower lining mobilization than oval and polygonal shafts.

Considering these conflicting aspects of traditional construction methods, a new solution was proposed that does not require the use of bentonite, struts or anchors: a large diameter shaft built by the sequential excavation method (SEM-Shaft). This technique creates a self-stable circular lining ring in direct contact with the ground mass, and both are mobilized for the system stability, much like the modern approach to tunnel design. The lining can confine the excavation as soon as the full ring is closed. However, in large diameter shafts, the perimeter might be too large and consequently demand a long time to be built. In these cases it is possible to pre-condition the soil and/or to install vertical piles along the perimeter, in order to support the ring segments until the ring can be finally closed (Celestino et al., 2009).

Single and multiple SEM-Shafts have been constructed for subway stations, mainly in Brazil and Portugal with remarkable technical and financial advantages over the traditional solutions (Celestino et al., 2009; França et al., 2004; Kuwajima et al., 2004a,b). However, the state of practice in the design of large diameter shafts often cannot cope with the structural and geotechnical complexities of the project, dissociating the two analyses and adopting assumptions that oversimplify the design models. Some design models only estimate the equilibrium stresses in the lining, assuming a distribution of the soil earth pressure and Winkler's springs, normally calibrated by a model developed for tunnels from Evison (1988). Other models evaluate the soil stability by verifying the earth pressure distribution against the Rankine limit states or by assuming the pressure distribution from the limit states with a certain factor of safety. Finite element model (FEM) calculations can consider soil-structure interaction and estimate soil displacements that these simpler models cannot predict. Two-dimensional (2D) finite element models can be processed and analysed in a relatively short time (Sozio, 2012), however the axisymmetric conditions generally disregard horizontal bending moments (Celestino et al., 2009) and cannot model some types of construction sequence nor inclined geological layers (Dias, 2011).

Therefore in this paper the authors present the results of parametric 3D finite element analyses of large diameter shafts and investigate the major effects of such a construction in terms of stress and displacements induced in the ground as well as the structural forces on the lining. Different construction sequences and geological profiles are simulated in order to assess their relative significance on the results. Different methods to evaluate the general stability of the lining system are also presented and compared.

2. Large diameter shafts

Campanhã and França (2008) describe the basic elements and the construction sequence of large diameter shafts. A diagram of the basic steps is shown in Fig. 3. In order to stiffen the shallow parts of the shaft and to enhance the stability of the initial excavation steps, a cast in-situ concrete edge beam is normally built. If water-bearing ground is present, then the excavation inflow and stability must be assured. Dewatering is an option when the ground is not contaminated and the consolidation settlements are acceptable. If not, soil enhancement might be necessary and the design of the primary lining should consider water pressures. The excavation advances in cyclic steps of excavation and casting

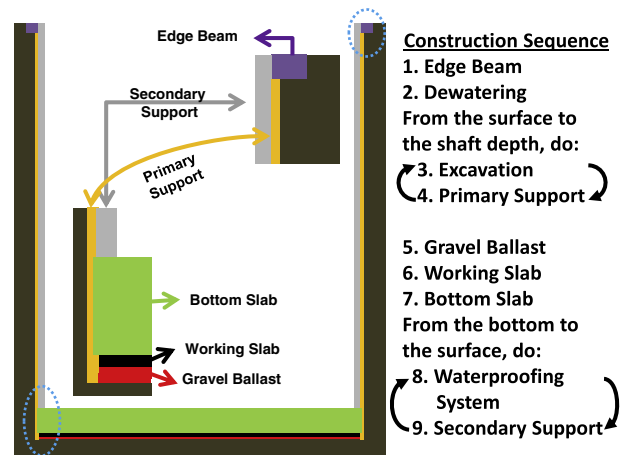


Fig. 3. Basic construction steps of a large diameter shaft.

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