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TWO NON-CONVENTIONAL PILED EMBANKMENTS IN BRAZIL

Introduction
Piled embankments are an interesting solution for soft soil environments, where the construction of conventional embankments is often associated with stability problems and/or excessive settlements. Instead of loading surficial soft soil, the embankment weight is carried by piles and founded on deeper seated, more competent soil layers. To improve the load transfer from the embankment to the piles, usually pile caps are used.

Principles
The main principle associated with piled embankments is soil arching. This important principle allows the use of discrete pile caps instead of a continuous slab. The principle is described in an illustrative way by Terzaghi in 1943 with the "trap door".

The Swedish Road Board (1974) is one of the first publications that presents an empirical design methodology. Hewlett and Randolph (1988) presented a landmark paper, with a sound theoretical approach, as well as experimental studies of the soil arching effects associated with piled embankments. Several other studies and publications are available about piled embankments.

The use of geosynthetics at the base of the embankments improved the performance of piled embankments, allowing the use of wider pile and pile cap spacing. Important publications that include the design of piled embankments with the use of geosynthetics are the British Standard BS 8006 (2010) and EBGEO (2011).

The landmark publication of Van Eekelen (2015) presents a new analytical design model, validated numerically and experimentally, for piled embankments with basal reinforcements. Van Eekelen's work was later adopted in the Dutch Design Guideline CUR 226 (2016).

In addition to arching between pile caps, for the successful use of piled embankments, horizontal forces are necessary to equilibrate internal earth pressures. Without geosynthetics, this equilibrium is usually achieved using raking piles. When using basal reinforcements in a symmetric geometry, horizontal self-equilibrating forces guarantee equilibrium. However, for non-symmetric geometries, like existing embankment enlargements, other measures are necessary to guarantee equilibrium.

Case Histories
The two presented cases are typical 'non-greenfield' projects, i.e., the piled embankments were built close to existing embankments, in a non-symmetrical geometry.
Design procedures were based on the methodology proposed in BS 8006, adapted by De Mello & Bilfinger (2004), adding effective cohesion to the soil shear strength. When embankments are built with lateritic soils, that present effective cohesion, a more economic design is possible when cohesion is included in the determination of the soil shear strength.

Case History 1
The project consisted of a highway enlargement with variable height. Local subsoil relevant for the project is very soft organic clay, so the construction of a conventional embankment was not possible due to potential stability and settlement problems. Figure 1 presents a simplified cross section, including the existing embankment and the embankment to be built.

For the design, the following key aspects had to be considered:
- an embankment with variable height;
- soft soil with variable thickness and shear strength;
- need to maintain part of the road operating;
- strict settlement criteria during the design life.

Figure 2 presents the design solution, that includes the following non-conventional features.
- A slightly sloping embankment base, to reduce the height of the cut on the left side of the figure, to avoid stability problems of the existing embankment, minimize interference with the operating road, and avoid excessive loads on the piled embankment.
- Anchoring of the geogrid in an area not founded on piles, to guarantee horizontal equilibrium.

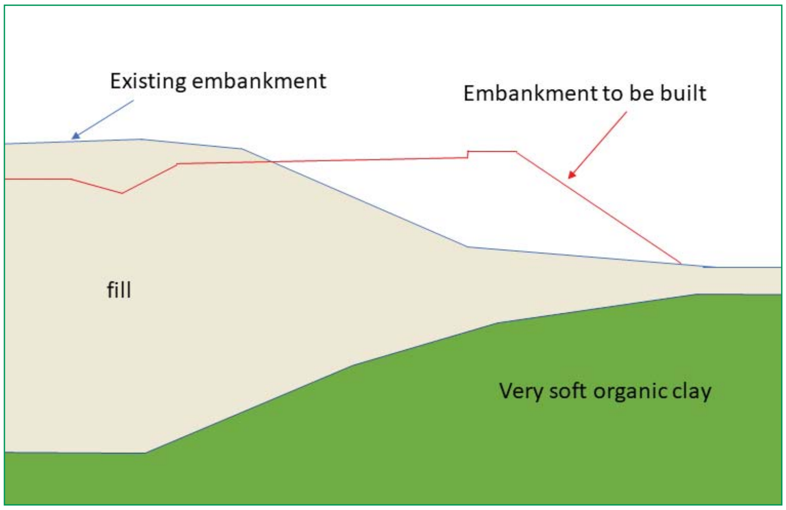


Figure 1 – Simplified cross-section of the existing embankment and the extensions to be built on very soft organic clay.

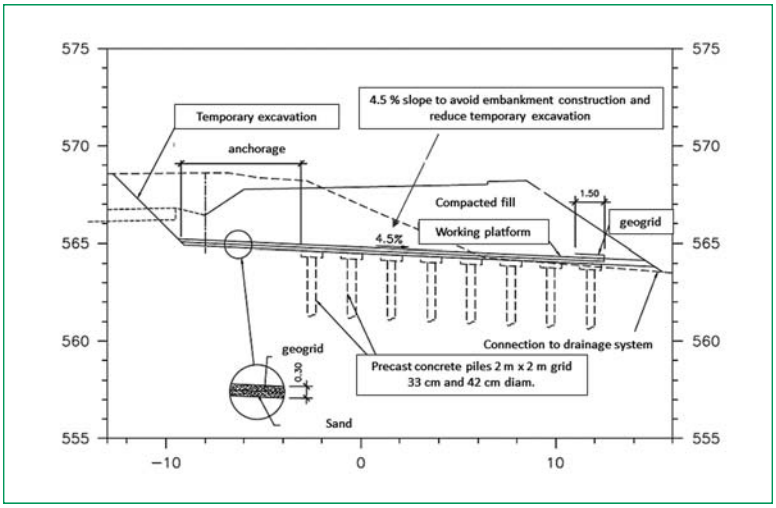


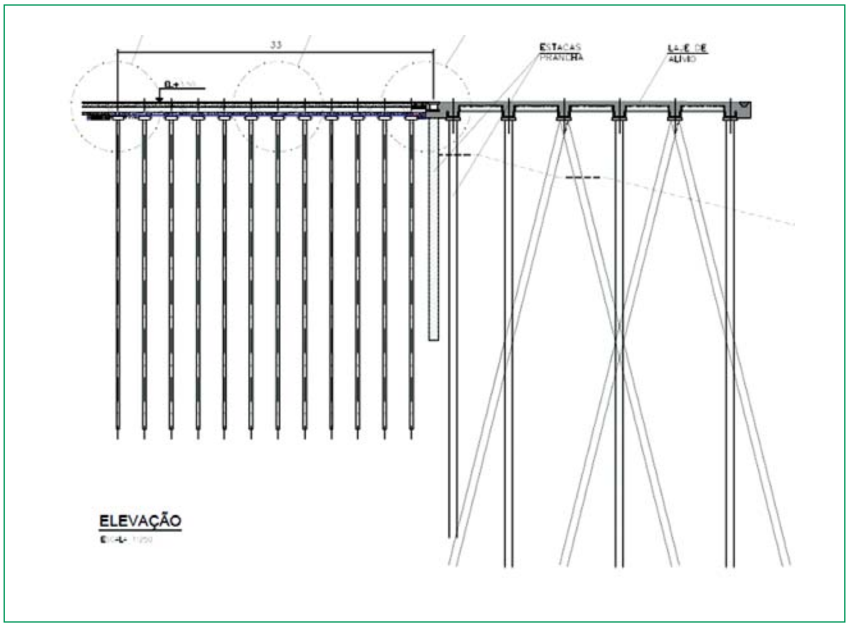
Figure 2 – Cross-section with the designed piled embankment, including a slope of 4,5% to limit groundworks as much as possible.

Due to the relatively stiff geogrids, the horizontal displacements were kept compatible with the pile behavior.
– Temporary partial removal of the existing embankment and extension of the piled embankment in this area, to reduce future settlements, especially in the region of the interface between the embankment with and without piled foundation.

Case History 2

The project consisted of a piled embankment built inside a container terminal. The major challenge of the project was the typical soil profile that includes more than 35 m of marine sediments, mainly soft to very soft clay.
During construction, excessive horizontal displacements (approximately 40 cm) of the sheet pile wall of the quay structure occurred. The problems were associated with the constructive sequence and unforeseen deeper seated very soft soil and led to the decision to temporarily avoid applying loads on the surface close to the quay structure. The chosen solution was the construction of a piled embankment, replacing part of the soft soil treatment (Prefabricated Vertical Drains + surcharge). Figure 3 presents a typical cross section of the piled embankment. Figure 4 presents a detailed view of the piled embankment and the interface with the quay structure.

Figure 3 – Cross-section of the designed piled embankment for a container terminal with 35 m of marine sediments.



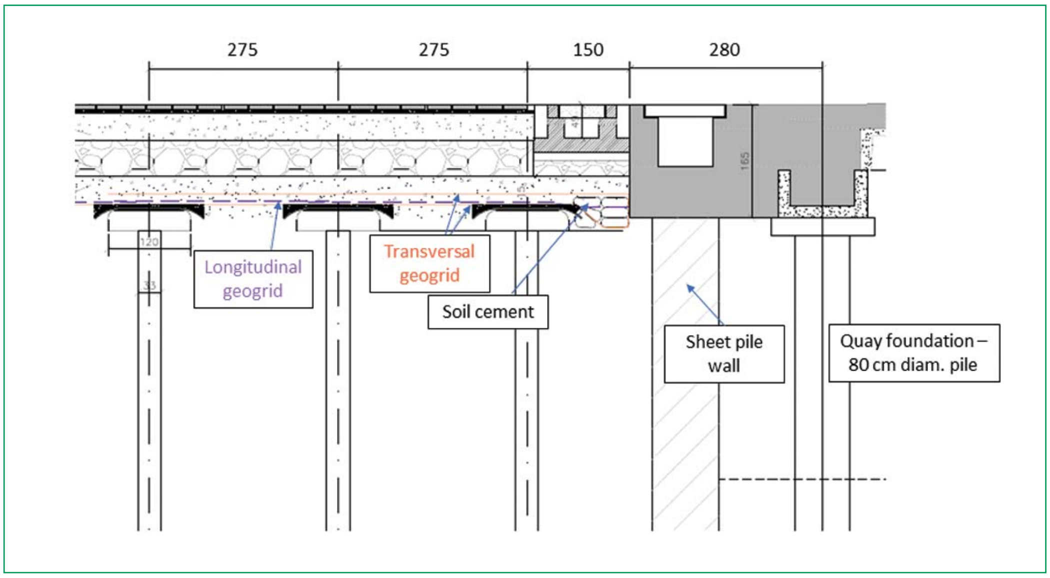


Figure 4 – Detail of the cross-section of the piled-embankment and the interface with the quay structure.

The design of the piled embankment included the following non typical characteristics:
– Relatively small embankment height (1.50 m).
– Highly variable surcharge, around 50 kPa, associated with the use as container terminal. Additionally, the position of the loaded areas varies frequently.
– Difficult anchoring conditions, especially at the interface to the quay structure.
– Some utilities, including culverts, had to be built inside the embankment.
– A residual settlement of the surrounding soil of 40 cm in 20 years was foreseen. For that reason, the piles of the piled embankment were designed as "floating piles", different from the piles of the quay structure, which were founded almost 20 m deeper, in residual soil.

To avoid tilting of the pile caps due to the possible non-symmetrical surcharges – equipment and containers at variable positions – the pile caps were structurally fixed to the specially reinforced concrete piles.

Concluding remarks

Piled embankments are proven geotechnical solutions and have been applied successfully for several decades. Design and construction methods evolved, which has led to more reliable and economic solutions.
For design and construction, in addition to soil arching between pile caps, with or without basal reinforcements, other verifications and design details may also be important. For example, non-symmetrical loads may generate non-foreseen pile cap movements, especially for low height embankments. Another important topic is the overall stability: in the case of non-symmetrical embankments, horizontal equilibrium may not be automatically guaranteed by symmetrically installed basal reinforcements.

Available design methodologies certainly do not explicitly include verifications for all possible conditions and, therefore, careful engineering judgement to evaluate possible non foreseen scenarios should always be part of design.

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