Sheet pile walls as a part of the substructure of bridges. Practical application in Denmark

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Abstract. The usage of "sheet pile wall" is very common solution in Denmark due to the geographic situation of the country – low sea level, a significant part of the state border is sea, high groundwater level, poor geotechnical conditions. The "sheet pile wall" is used for strengthening of embankments, reclaim marine territories and as a supporting walls of railway lines and roads. As a consequence of this, a very common solution is to use the sheet pile walls as a part of the substructure of bridges – overpasses of railway lines and roads when the alignment is in excavation. From one side, the "sheet pile wall" are used as wing walls of the bridge and they support the road embankment. From another side, it is used as an abutment walls of the bridge. The part of the wall acting as a bridge support is design with some concrete "hammer beam". The "hammer" in some cases is connected to the bridge deck by means of concrete hinges. Very often, "sheet pile wall" in the zone of the wing walls is combined with anchors in order to take increased section forces. Common variants in Denmark practice for connection of the bridge superstructure and sheet pile substructure are presented and analysed in the paper.

1 Introduction

The application of steel sheet pile walls into the substructure of bridges is not uncommon in contemporary practice [1-3]. In integral bridge designs, the superstructure typically ends with a steel-reinforced concrete element securely linked to the sheet pile wall, serving as the foundation. It is possible to have a combined reinforced concrete or steel element, firmly connected to the sheet pile that may serve as the load-bearing surface for the superstructure (utilizing corresponding devices such as elastomeric bearings, pot bearings, or reinforced concrete joints, etc.). Figures 1, 2, and 5 illustrate bridge configurations featuring sheet pile wall foundations drawn from European practice. Figures 3 and 4 showcases a road bridge in Beverungen, Germany, with a monolithic reinforced concrete slab superstructure of L=7m [4].

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The CROWN/APEX of the sheet pile wall is embedded 150mm within the reinforced concrete slab of the superstructure (knife-edge bearing). According to the European standards when calculating steel sheet piles, the requirements of EN 1993-5 and EN 1997 should be followed.

Given the susceptibility of steel to corrosion, appropriate materials must possess adequate corrosion protection (zinc coatings, polymer coatings, etc.), ensuring longevity within the prescribed design service life. Requirements regarding steel for hot-rolled sections for steel sheet pile walls are standardized in the European standard EN 10248-1

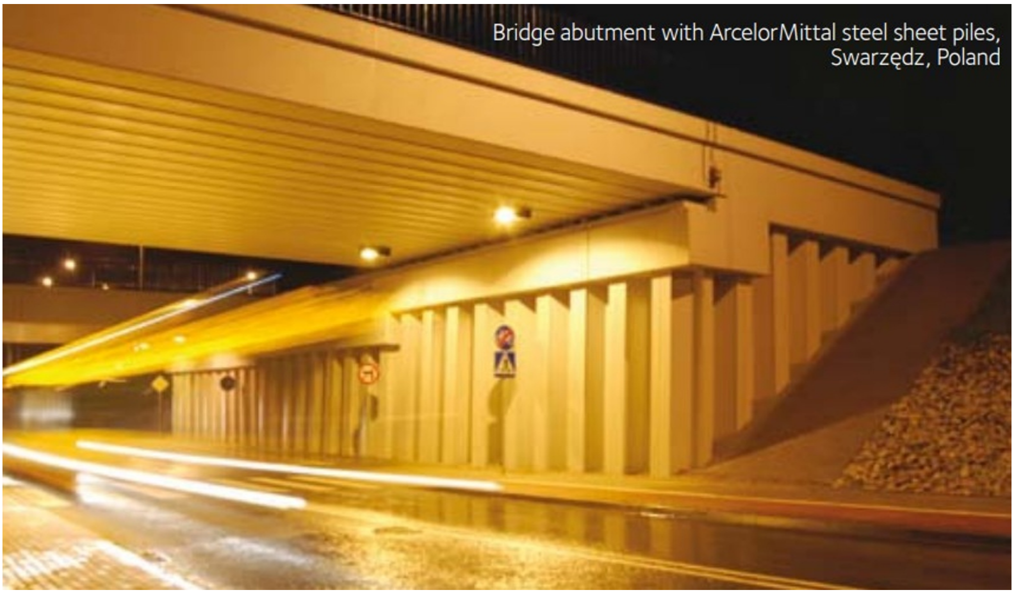

Fig. 1. Overpass with steel sheet pile wall foundations in Poland.

Fig. 2. Bridge with integral abutments consisting of steel sheet pile walls and a steel-reinforced concrete connecting beam.

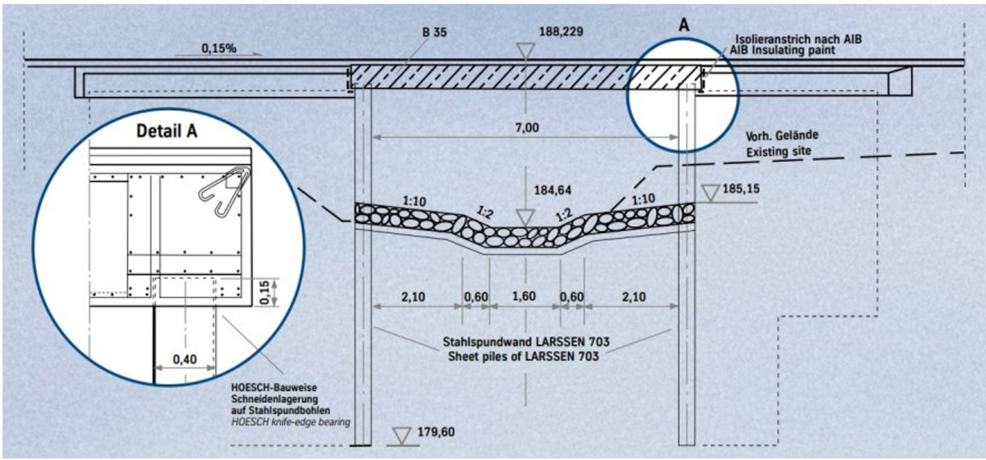

Fig. 3. Bridge with a 7m span, Beverungen, Germany (knife-edge bearing).

Fig. 4. View of abutment consisting of steel sheet pile LARSSEN 703 SP on a bridge with a 7m span.

Fig. 5. Overpasses above the high-speed railway line Copenhagen-Ringsted, Denmark.

On Figure 7 is depicted an underground structure (shallow-buried tunnel), with a length of 310m, from which 160m are covered with a steel-reinforced concrete top slab. The vertical walls consist of steel sheet pile walls, joined at their upper ends with a steel-reinforced concrete beam. Such type of structure is often defined as a shallow-buried tunnel, but in fact, it represents a backfilled bridge with a width significantly exceeding the span.

Depending on the aggressiveness of the environment, the loss of thickness from the cross-section of the steel sheet pile due to corrosion can range from 0.01 to 0.02mm per year (according to EN 1993-5: 2007). Depending on the location relative to the water level (corrosion zones are defined) and the aggressiveness of the environment, this rate can be significantly higher. The main factors influencing the rate of corrosion-induced thickness loss include soil type, variations in water levels (freshwater and saltwater), the presence of oxygen, and the presence and concentration of other aggressive pollutants. According to EN 1993-5:2007, the loss of thickness due to corrosion should be accounted for in the structural calculations of steel sheet piles as a function of the design service life. In Figure 1.6 is a steel-reinforced concrete bridge with integral abutments consisting of steel sheet pile walls (Poland, constructed in the early 20th century), demonstrating the durability of such a solution [5].

The main advantages of using a steel sheet pile wall as the foundation for a bridge structure compared to the standard solution with reinforced concrete abutments are:

Speed of execution compared to other options for building structures.

- There is no need for forming a slope as with standard excavation, which reduces earthworks and requires a smaller alienation zone, wet processes are absent or minimized, thus minimizing environmental pollution around the construction site. Due to their greater compactness, they are suitable for constructing bridge abutments in urban conditions.
- The relatively greater deformability of steel sheet piles results in lower forces from temperature changes (and other influences) due to the frame effect in integral or semi-integral bridges compared to classical steel-concrete abutments [4].
- Sheet pile walls can effectively be used in high groundwater levels or water obstacles without the need for complex drainage activities in excavations.

Fig. 6. Bridge with integral abutments - sheet pile walls from the beginning of the 20th century.

Fig. 7. Underground structure with walls - steel sheet piles in Brazil.

2 2 Application of substructure made of sheet pile walls for bridges in Denmark

The application of sheet pile walls in Denmark is widely spread due to the country's geographical location - low altitude, a large percentage of the country's border is coastal, high groundwater levels, and poor geological conditions. They are used for shoring excavations, reclaiming coastal areas, as well as for retaining walls along roads and railway lines. As a result of the aforementioned, a very common solution is for sheet pile walls to be part of the substructure of overpasses above roads and railway lines in excavations. On one hand, sheet pile walls are used as "wings" of the structure, therefore they support the embankment behind the wall. On the other hand, they are used as abutments of the structure. Further, two typical examples of a road and pedestrian overpass above the high-speed railway line Copenhagen - Ringsted (design speed 200 km/h) are presented, developed with the participation of the authors.

Figure 8 shows a reinforced concrete skew bridge, made of ordinary concrete with a span of approximately 13 meters (L~13m). The upper structure consists of a reinforced concrete slab forming a trough together with vertical walls, supported by reinforced concrete hinge connections on a unifying reinforced concrete beam (cap beam), firmly connected to the sheet pile wall, serving as an abutment. The presence of backfill increases the dead load of the bridge but is favorable to avoid sharp transitions in the vertical curvature of the road inside and outside the bridge, as well as minimizing the dynamic effects from traffic on both the upper structure and the sheet pile wall - Figure 9. In the bridge area, besides the earth pressure, the sheet pile wall should also bear the vertical and horizontal reactions from the upper structure, which is a reason for the greater depth of penetration - Figure 10.

The sheet pile wall is approximately 8 meters high, and it is necessary to incorporate anchors in order to displacements and to consider shear forces - Figure 8 and Figure 10reduce horizontal.

Fig. 8. Road overpass L~13m with integral abutment (Copenhagen-Ringsted railway line), Denmark.

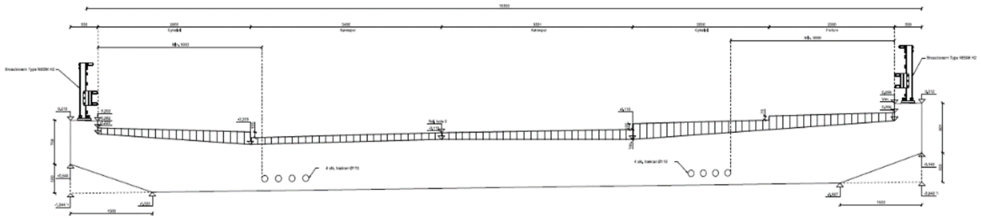

Figure 9. Cross-section of the bridge structure.

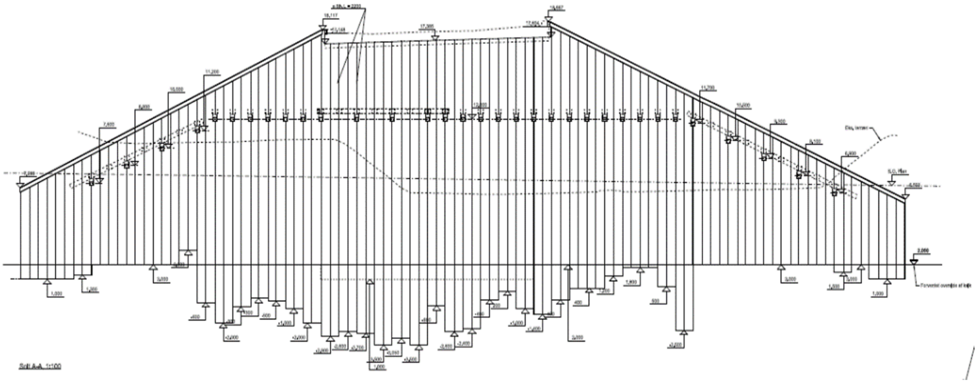

Figure 10. Steel sheet pile wall in the area of the bridge structure.

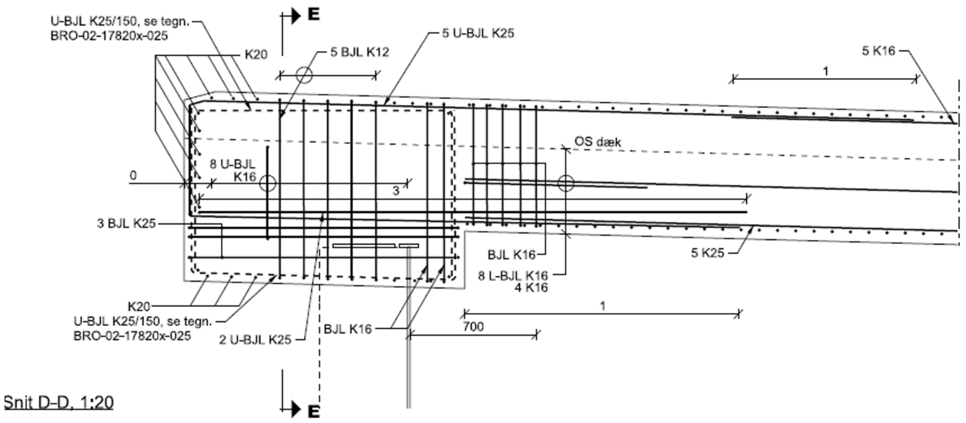

Figure 11. Detail of the connection between the superstructure, cap beam, and steel sheet pile.

Figure 11 illustrates the detail of the connection between the superstructure and the steel sheet pile wall, ending with unifying reinforced concrete beam. The hinged connection between the upper structure and the unifying beam is achieved through a steel-concrete hinge along the bearing line, allowing for relatively free rotation of the substructure. The unifying beam serves to support the superstructure and to achieve a more even distribution of vertical loads along the length of the sheet pile wall. The structural calculations and detailing are carried out in compliance with the requirements of the Eurocode system and the relevant Danish national annexes. The interaction between the sheet pile wall and the soil mass is accounted for using nonlinear springs with properties corresponding to the characteristics of the respective soil layers.

Figure 12 displays two single-span steel pedestrian bridges (made of S355 steel according to EN10025-2), supported on sheet pile walls via elastomeric bearings. The superstructures of the two bridges are similar. Figure 13 illustrates the supporting of the upper structure through neoprene bearings on a steel plate with a thickness of 40mm welded to the top edge of the steel sheet pile. By definitive requirement from the client, considering maintenance specifics and the desired appearance, the substructure consists of simply supported six-point steel box girders with an orthotropic deck featuring trapezoidal longitudinal ribs. The cross-section is depicted in Figure 14. The road structure consists of an orthotropic steel deck with a thickness of 10mm, ribbed with trapezoidal longitudinal ribs and solid transverse beams. The described constraints lead to a relatively complex execution of the steel box orthotropic upper structure. Due to the small opening and the height of the upper structure of the bridge being relatively small (h=500mm), there is no possibility for access inside the box. The trapezoidal longitudinal ribs are welded around their perimeter to the solid transverse beams - Figure 16. This detail is acceptable for pedestrian bridges where the intensity of cyclically variable live loads is relatively low. The openings provided in the transverse beams are for air circulation. Figure 16 also shows the detail for connecting the intermediate stem of the box with the steel plates forming the bottom flange of the box girder, similar to the detail of the connection between the solid transverse beam and the bottom flange of the girder and dictated by the lack of access inside the box. In this configuration, the solid transverse beam is subjected to tension perpendicular to its thickness, and therefore, additional requirements for class Z15 for lamellar tearing according to EN 1993-1-10 are expected to be applied to the steel. The calculations for the upper structure have been conducted in accordance with EN 1993-1-1 and EN 1993-2The less critical welds, which do not affect the sealing of the box, are in accordance with the provisions of EN 1993-1-8.

The elastomeric bearings are of Type C according to EN 1337-3. The bearing capacity of the sheet pile walls is ensured through adequate anchoring. Computational checks for the sheet pile walls are conducted in accordance with the provisions of EN 1993-5 and EN 1997

Figure 13. Support of a steel pedestrian bridge on elastomeric bearings.

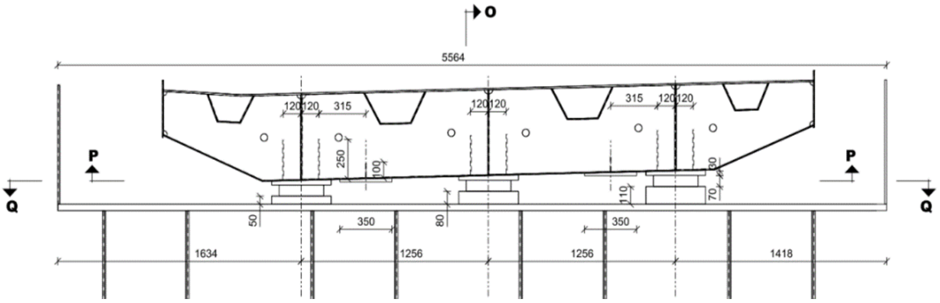

Figure 14. Stepping of a steel pedestrian bridge on a steel plate welded to the upper edge of the sheet pile wall.

3 Conclusion

Sheet pile walls as part of the substructure of bridges (conventional or integral abutments) are effective and are frequently applied in European practice, particularly in road and pedestrian bridges with small openings in excavations. Due to specific terrain and hydrogeological conditions, this option finds widespread application in Danish construction practice. It is noteworthy that the use of sheet pile walls for bridge abutments with small openings is easy, fast, and technologically advanced, associated with maximum compactness of the construction site and significant reduction in wet processes, thereby positively impacting environmental pollution minimization. Usually, the connection detail between the upper structure of the bridge and the sheet pile wall is relatively complex, and its calculation and structural design require serious attention to optimize the behaviour of the structure. Additionally, the relative flexibility of sheet pile walls reduces adverse effects from temperature variations associated with the frame effect in integral bridges. Due to the compactness of the construction site and the speed of execution, such a solution can be effective in bridge construction in urbanized areas or other constrained conditions (such as property ownership and alienation issues). The possibility of using sheet pile walls as part of the substructure of bridges with small openings should be seriously considered in conceptual design, as in certain cases, it may be more effective than other standard solutions.

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