Recent Advances in Bridge Engineering – Application of Steel Sheet Piles as Durable Structural Elements in Integral Bridges

P G Kossakowski

1Department of Strength of Materials, Concrete and Bridge Structures, Faculty of Civil Engineering and Architecture, Kielce University of Technology, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

Abstract. This paper discusses some of the problems related to the design and construction of integral and semi-integral bridges and the potential use of steel sheet piles as their permanent structural elements. The study focused on analyzing a recent application of this approach to support two overpasses in the TS-1 tunnel project completed in Kielce, Poland. The findings concerning the load-carrying capacity of steel sheet piles acting as supports indicate that this solution has a very high potential and it can be used on a much larger scale, not only in integral bridges but also in buildings and other non-building structures.

1. Introduction

Integral bridges are one of the most dynamically developing civil engineering structures, continually improved over time. Of interest is the fact that design concepts for integral bridges may involve the use of the latest structural systems and materials, e.g. high-strength steels, concretes or composites.

Structural durability has been an important factor determining the direction of research in this area for over a century. Actually, there have been two major trends: one focusing on the reduction in construction costs and the other on the reduction in maintenance costs. When a bridge has a service life of about 100 years [1], these problems become particularly crucial. Inspections of old bridges, older than 100 years, reveal that their condition is frequently poor, i.e. their load-carrying capacity and fatigue strength are no longer sufficient [2].

The research findings show that the phenomena responsible for the structural failure and, consequently, a shorter service life of a bridge are first observed at structural discontinuities. An example of these is the expansion joint between the bridge deck and the embankments. Some approaches to solving this problem assume that no expansion joint can be used; this means that the bridge needs to be designed and constructed as a continuous structure. Such bridges are called integral bridges, and their main feature is that there are no movement joints between the spans and the abutments in order to prevent relative horizontal displacements. Although integral bridges are usually designed as single-span structures, a multi-span continuous option is also possible. Most structures of this type are made of mass concrete.

The concept of integral bridges is not new in bridge engineering; the first studies were conducted in Great Britain and the US as early as in the 1930s. The first integral bridge was the Teens Run Bridge built in 1938 near Eureka in Gallia County, Ohio, US. Its five continuous spans made of reinforced concrete are supported by capped pile piers and abutments [3]. The idea of integral bridges has spread across the world. In Asia, for instance, the first integral bridges were constructed around the turn of the 21st century (Japan 1996, South Korea 2002). However, the country where integral bridges have become a common solution is Great Britain [4]. The recently completed integral bridges include the
Unstrut Valley Bridge in Germany, the bridges of the A1 motorway in Romania as well as the Dankuni-Palsit Flyover and the Kalkaji Flyover in India.

Many research centres and management companies, for example, those described in [5-13] are involved in improving the concept of integral bridges, because there are still many problems to be solved, such as problems related to the assessment of the ultimate limit state. The context of failure prediction based on damage mechanics (e.g. [14-16]) is important in this case. One of the areas of development of bridge structures is the introduction of elements that have had different applications, not even as structural members. An interesting and innovative solution is the use of steel sheet piles to build bridge abutment walls, which is the subject of this paper. There are very few bridges where steel sheet piles are used as integral structural elements; the examples in Poland include the abutments of the railway bridges in Lewin Brzeski and Swarzędz and the road bridges in Rzeszów and Kielce. In the Kielce project, described in this paper, the overpasses above the TS1 tunnel are some of the Polish biggest bridges where steel sheet piles were used as permanent structural elements. Obtaining a required load-carrying capacity of sheet piles as supports, and consequently, constructing a bridge with a considerable span length are significant achievements in the area of integral bridges.

2. Application of steel sheet piles as integral elements in buildings and non-building structures

Steel sheet piles are commonly used in the construction industry. In bridge engineering, their applications are numerous. Generally, they are employed as temporary walls to support excavations in various civil engineering projects. They are also suitable as elements protecting bridge piers and pier foundations from water action. For some time now, steel sheet piles have been introduced as permanent structural elements. In certain types of structures, steel sheet piles have become common as the main or self-supporting structural elements. However, globally, the number of projects with structures employing steel sheet piles on a regular basis is not high. In most cases, steel sheet piles are used as temporary elements supporting excavations.

Obviously, steel sheet piles have many benefits, which is why researchers and engineers are considering how to extend their applications. Steel sheet piles can be used in a number of complex civil engineering structures to solve specific problems and overcome certain limitations. A frequent problem encountered during construction or reconstruction of bridges located over operating rail lines or during maintenance, repair or removal of rail tracks is that the time limit allocated for such work is very short. Under such circumstances, it is not technologically feasible to use traditional reinforced concrete abutments; it is essential to look for alternative solutions offering, for example, fast installation of elements. One option is steel sheet piles, where the assembly time is indeed very short. The financial aspects of bridge projects based on sheet pile profiles are also very important, sometimes, more important than the engineering aspects. Another significant feature of this solution is that sheet piles have a double role when used as permanent structural elements: they protect excavation from collapsing during and after construction and they contribute to lower total costs because there is no need for their removal.

The benefits of steel sheet piles were noticed a long time ago. Initially, they were applied as self-supporting and main structural elements. Over the recent years, however, the solutions implemented globally have included tunnels, bridge abutments and underground car parks, where sheet piles constitute part of the structure. A good example of such a structure is a car park in Bristol constructed in 1999, where steel sheet piles were used as the walls. In Poland, steel sheet piles have been applied as permanent integral structural elements only recently.

3. General information on the TS-1 tunnel

The civil engineering structure discussed in this paper is the TS-1 tunnel with two overpasses. The project was completed in Kielce in 2011 [17]. It is part of the eastern exit from one of the Poland’s main expressways, i.e. road S74. As was assumed at the design stage, the entire section of the exit from S74 was constructed to have parameters of an expressway, e.g. grade-separated junctions. The same rules were followed for the urban interchange of expressway S74 and national route DK73, where the TS-1 tunnel is situated. At this two-level interchange, road S74 was designed and constructed to run below road DK73. As a result, road DK73 includes two overpasses above the TS-1
tunnel. The solution to build an interchange in the form of a tunnel is not a novel concept; yet, the overpasses above the TS-1 tunnel in the form of single-span bridges comprising a system of T-beams made of prestressed concrete supported on steel sheet pile walls is definitely not a common solution in Poland. The entrance to the TS-1 tunnel is located in the middle of the Świętokrzyska section between Warszawska Street and Solidarności Alley. As mentioned above, the tunnel constitutes a section of road S74 above which there are two overpasses for road DK73 (figure 1a). The two-level interchange of roads S74 and DK73 was designed as two separate bridges: eastern overpass above the road in the direction of Warsaw and the western overpass above the road in the direction of Tarnów.

Figure 1. (a) The TS-1 tunnel and the western overpass (view from the west); (b) Cross-section of the eastern overpass above the TS-1 tunnel with a detail of the supporting sheet pile wall [basing on 18].

4. Design assumptions – the use of steel sheet piles to construct the TS-1 tunnel walls

Different design and construction options were considered for the eastern exit from expressway S74 from Kielce. One of the basic problems encountered was complex soil conditions over the section including the TS-1 tunnel. The in situ tests showed that the soils used for the embankments included construction debris and subsoil (extending up to a depth of 1.8 m). Below that depth, the soil in the tunnel area is: non-cohesive (fine and medium sand, ranging from semi-compact to compact), cohesive (loamy sand, sandy clay, clay, and compact clay ranging from plastic to semi-solid) and rocky (at a depth of 13÷15 m) [19]. In most test holes, ground water was also present. Because of the complex soil and ground water conditions, it was necessary to install retaining walls with anchors placed in the soil to protect the tunnel excavation and to build a drainage system. The structure was classified as category II. The decision to use steel sheet piles to build the excavation wall resulted both from the soil and ground conditions and the economic aspects. The costs of construction of traditional retaining walls and bridge supports made of reinforced concrete were higher than the costs of construction of sheet pile walls. The function of the sheet pile walls was to support excavation during construction and to support the bridge above the tunnel. One of the main reasons for this solution was the high load-carrying capacity of steel sheet pile walls to withstand vertical loads. The ground water conditions required designing and building a tunnel drainage system including a drainage ditch along the entrance to the tunnel.

5. Details of the TS-1 tunnel structure

The two separate bridges, the eastern and western overpasses, constituting a section of national route DK73, were used as part of the roof of the TS-1 tunnel. The overpasses were single-span bridges with a horizontal clearance of 24.4 m, designed and constructed as a system of T27-type prefabricated prestressed concrete beams with a height of 110 cm spaced every 90 cm (figures 1a and b). The beams were supported on sheet pile walls and linked to them using caps (0.90 m in height and 0.85 m in width), fixed at the coping level, to form a frame system. The bridge deck with a thickness of 25 cm
was made of reinforced concrete cast in-situ over the T27-type prefabricated pre-stressed concrete beams. C30/37 concrete and B500SP reinforcement steel were used for that purpose. The space between the eastern and western overpasses was shaped with the bridge deck; it was used to construct the inner corners of the spans and the retaining walls. The bridge entrance ramps were designed and constructed to have transition plates with a length of 5 m and a thickness of 25 cm. The entrance ramp is linked to the bridge using a bitumen expansion joint, whose role is to receive horizontal displacements ranging from –4.72 mm to +4.05 mm. The bridge deck was insulated using torch-applied modified bitumen membrane with a thickness of 5 mm. The pavement was designed to have two layers: the binder course, whose function was also to level irregularities at the roundabout, made of hard paving grade bitumen with a thickness of 5-8 cm and the surface course made of stone mastic asphalt (SMA) with a thickness of 4 cm.

According to the design and construction assumptions, the excavation was protected with steel sheet pile walls along the whole length of the TS-1 tunnel and the access roads. Cantilevered retaining walls were used at the initial sections of the tunnel entrance and exit, up to a depth of about 2.5 m. In the other sections, the walls were additionally reinforced by means of anchors placed in the soil.

Although steel sheet piles are used not only to protect excavation walls in different civil engineering structures but also as permanent structural elements, their application as abutment walls in bridges is a completely new solution in Poland, because of the size and function of the structure. Initially, it was assumed that the excavation walls and bridge abutments should be constructed using VL 604-type steel sheet piles. During installation, however, a decision was made to replace them with Z-type steel sheet piles (AZ 17 and AZ19 profiles shown in figures. 2 a, b and 3) produced by Arcelor Mittal.

The reason for that was a number of benefits that AZ 17 and AZ19 profiles offer, and these include high strength parameters (because of the web continuity and symmetric distribution of joints), a high elastic section modulus to mass ratio, a high moment of inertia corresponding to lower deflections, faster assembly because of a large profile width and, finally, high durability. The values of deterioration in the form of thickness losses for steel sheet piles attributable to corrosion taking place in dry or watered ground was estimated according to the standard EN 1993-5 [20].

![Figure 2](image1.png)  
**Figure 2.** Geometry of an Arcelor Mittal AZ sheet pile profiles: (a) AZ 17; (b) AZ 19 [19].

![Figure 3](image2.png)  
**Figure 3.** Structural cross-sections of the sheet-pile walls of the TS-1 Tunnel: (a) sheet-pile excavation wall; (b) eastern overpass.
The driving technology was also very important. Steel sheet piles were driven using static jacking. An interesting problem from the design point of view is the load-carrying capacity of the steel sheet pile walls to withstand vertical forces; they are used as the support elements of the bridge to carry the considerable weight of the bridge itself (dead load) and the weight of the moving vehicles (live load). The selected sheet piles possess a high vertical load-carrying capacity, which enables the transfer of loads occurring along the width of the bridge. The load along the width of the abutment walls may amount to 881.9 kN per 1 m.

6. Conclusion

The TS-1 tunnel described in this paper is an example of one of the first Polish structures where steel sheet piles were used as durable structural elements for abutment walls. As bridges are subjected to higher and higher loads, resulting from an increase in road transport intensity, and they are more widely exposed to pollution, their condition may sometimes be unsatisfactory and they may be approaching the end of their service life. In the TS-1 tunnel project, one of the major structural problems to be solved was to reduce the number of places where destructive processes could occur. It was decided that continuous integral structural elements, i.e. sheet piles, should be used as supports. This solution can be regarded as a significant step forward in the development of integral bridges. It was essential, however, to predict the load-carrying capacity of the supports. The load-carrying capacity of steel sheet piles subjected to vertical loads has been studied since the last century. The engineers working on the TS-1 tunnel project not only approached the problem theoretically but also conducted experiments on laboratory- and real-scale models under test loads. The results were used to develop methods for determining the load-carrying capacity of sheet pile profiles. These findings can be employed to determine the load-carrying capacity of sheet pile walls used in the construction of bridges with any span length.

The TS-1 tunnel constructed as an integral bridge seems to be an optimal alternative for the future development of bridges. This structural solution should now be implemented on a larger scale; it should inspire both design and construction engineers to apply sheet piles in similar civil engineering projects.

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