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EXPERIENCE WITH SLEEPER SUBSTRUCTURE DESIGN FOR A SPEED OF 200 KPH ACCORDING TO THE S4 STANDARD

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Abstract. The paper deals with the sleeper substructure design for a speed of 200 kph according to the Czech SŽ S4 standard. The paper includes the design of sub-ballast and capping layers. The second part of the paper is focused on transition area design. The conclusion brings recommendations of alterations which would be appropriate to incorporate into the standard.

Keywords: Sleeper substructure design, sub-ballast layer, capping layer, transition area, deformation resistance, SŽ S4 standard.

1. Introduction

This paper is derived from practical experience with the sleeper substructure design for the modernization of the track Brno – Přerov (for one of the project stages used within the Czech Republic). This is one of the first practical examples where the design for a track speed of 200 kph is being considered together with the fact that in the vast majority of the section the design uses a new track body with a new track alignment. In the Czech Republic, there is not much practical experience with such a design and thus it is possible to practically "verify" the design methodology according to the new S4 standard for this speed. Particularly, the project was focused on the 2nd and 3rd sections between the railway station Blažovice and the railway station Nezamyslice. Considering the track geometry of the existing railway track, outside municipality borders it is essentially a design of a new railway line only "returning" to the existing stations in their current or near location inside municipality borders.

2. Geology

The geology of the interest area is not very favourable in terms of the design of the sleeper substructure. This is the area of the Outer Carpathian foredeep, which was formed at the junction of the Bohemian Massif and the Carpathian System, and is mainly formed by sandy limestone and claystone. These Tertiary rocks are overlain by Quaternary fine-grained sediments, namely loess, loess clay and clay. Coarse-grained sediments (sand and gravel) also occur in the area of the watercourses [1].

3. Geotechnical Survey

The geotechnical survey carried out along the designed route confirmed the assumption of fine-grained soil occurrence at the future earthworks level. Specifically, clay with medium to high plasticity (F6 CI and F8 CH) predominated along the entire length of the route. To a significantly lesser extent, other fine-grained clayey and loamy soils were also represented. Locally the bedrock was observed, namely limestone in various degrees of weathering. Exploration wells were carried out in the existing stations, which revealed clayey soils of insufficient bearing capacity furthermore, in contrast to the track sections, static plate load tests were also carried out in the existing stations by the established practice to persist their current position.

4. Values of Static Deformation Modulus

In the track sections, the values determining the deformation resistance of the earthworks level were not directly available, therefore the values of the static deformation moduli for individual soils were taken from the S4 standard [2], appendix 9, table 3 (see Figure 1). For the most frequently used soils, i.e. clay with medium to high plasticity, the tabular Indicative static deformation modulus values E_{ZP} are very low, in the range between 2–4 MPa.

In the current station sections, although there has been long-term consolidation since their construction, some static plate load tests came out surprisingly unfavourably: in many places the reduced static deformation modulus was just $E_{0,r} = 5$ MPa, which is far below today's requirements for the bearing capacity of the earthworks level.

5. Design of Sub-ballast Layers and Capping Layers

The design is strongly affected by the discrepancy between the very low values of the static deformation modulus of the original soil and the high requirements for the static deformation modulus of the earthworks level. For example, the requirement for the main tracks (speed 200 kph) on the earthworks level is $E_{min,ZP} = 70$ MPa, and on the railway platform $E_{min,PL} = 90$ MPa. The fulfilment of such requirements, therefore, resulted in the necessity of designing

Tabulka 3 – Orientační stanovení charakteristických hodnot modulu přetvárnosti a obvyklé hodnoty zemin dle jejich klasifikace

Název zeminy dle ČSN 73 6133, resp. přílohy 10 1)	Symbol 1)	Obvyklé hodnoty zemin podle jejich klasifikace: Proctorova zkouška – max. objemová hmotnost (suchá) $\rho_{d\ max,PS}$	Proctorova zkouška – optimální vlhkost $w_{opt,PS}$	Poměr únosnosti CBR – při optimální vlhkosti	Poměr únosnosti CBR – po uložení ve vodě	Orientační charakteristické hodnoty modulu přetvárnosti E_{ZP} 2) 3)
		[kg.m^{-3}]	[%]	[%]	[%]	[MPa]
zeminy jemnozrnné (F > 35%)						
hlína štěrkovitá	F1 MG	1550 - 1900	10 - 25	5 - 25	5 - 15	15
jíl štěrkovitý	F2 CG	1550 - 2000	12 - 30	5 - 20	3 - 10	10
hlína písčitá	F3 MS	1600 - 2000	10 - 30	5 - 25	5 - 15	8
jíl písčitý	F4 CS	1550 - 2000	12 - 35	5 - 25	5 - 15	7
hlína s nízkou plasticitou	F5 ML	1600 - 1800	12 - 20	5 - 20	0 - 7	5
hlína se střední plasticitou	F5 MI	1500 - 1750	15 - 25	5 - 20	0 - 7	5
jíl s nízkou plasticitou	F6 CL	1600 - 1950	10 - 30	3 - 15	0 - 7	4
jíl se střední plasticitou	F6 CI	1550 - 1900	15 - 35	3 - 15	0 - 7	4
hlína s vysokou plasticitou	F7 MH	1400 - 1700	15 - 33	5 - 15	0 - 5	3
hlína s velmi vysokou plasticitou	F7 MV	1380 - 1650	20 - 35	5 - 15	0 - 5	3
hlína s extrémně vysokou plasticitou	F7 ME	1350 - 1550	22 - 38	5 - 15	0 - 3	3
jíl s vysokou plasticitou	F8 CH	1380 - 1700	17 - 37	3 - 12	0 - 3	2
jíl s velmi vysokou plasticitou	F8 CV	1360 - 1650	19 - 39	3 - 12	0 - 3	2
jíl s extrémně vysokou plasticitou	F8 CE	1330 - 1500	20 - 40	3 - 10	0 - 3	2

FIGURE 1. Examples of indicative static deformation modulus values determination [2].

a multiple capping layer system of relatively substantial thickness. In practice, this meant that apart from the sub-ballast layer, the design of at least one or even two capping layers was necessary. The sleeper substructure layers are shown schematically in Figure 2.

As the basic capping layer, soil enhancement was chosen, with the decision that, in the event of the need to design more base layers, the bottom layer will be made using on-site mixing technology, and the above layers will then be made in the mixing centre of soil excavated from the subsoil. Due to the scale of the planned construction, we emphasized economy and ecology during the design, so the choice of soil enhancement turned out to be the best option. In the case of an on-site soil enhancement layer, there is no need to excavate the existing earth mass, there is no need to transport large amounts of other materials to the construction site and also there is no need to use new crushed aggregate, which is already in short supply today. Therefore, it is an economic and also ecological option with no need for large volumes of movements. Enhanced soil cannot be used in places where adverse effects of water and frost are to be expected. Thus, in locations where these adverse circumstances were encountered, capping layers of crushed aggregate were proposed instead of soil enhancement.

However, from a design point of view, capping layers of crushed aggregate suffer from a disadvantage in the form of the need for deeper railway ditches, which then increase the volume of excavated soil, and also increase the occupation of the necessary land.

In the first phase of the design, the sub-ballast layers were implemented according to Table 3 of Appendix 6 of the S4 standard (see Table 1).

6. Transition Areas

In the next phase of the design, the placement of railway substructure objects (such as bridges and tunnels) located on the railway track route was included. Ahead of and behind these objects, a transition area of the railway substructure must be designed to ensure a smooth transition of stiffness in the substructure. The design of transitional areas is described in Appendix 24 of the S4 standard [2].

For new objects, a transition area is designed using a transition wedge and backfilling of the transition area. This means that the construction of the sleeper substructure itself remains the same as in the previous section, and the increase in stiffness is obtained using more load-bearing soil of a considerable thickness as it is described in Appendix 24 of the S4 standard. For any object embedded in the embankment, this approach is natural, however for objects preceded by a cutting, such as tunnels, the replacement of the soil to increase the stiffness makes no practical sense. Despite this fact, Appendix 24 of the S4 standard does not specify the arrangement of the transition area ahead of and behind the new tunnel constructions, where due to the deep cutting linked to the tunnel portals excavating the soil under the sleeper substructure to a greater depth does not contribute to the quality of the design. The answer can be found in Appendix 24 of the S4 standard, which states that in the case of tunnels, a reinforced sleeper substructure (the standard uses an abbreviation ZKPP) is proposed. It would be appropriate to include this information directly in Appendix 24, which deals with transition areas in detail.

In the case of existing tracks (and newly built tun-

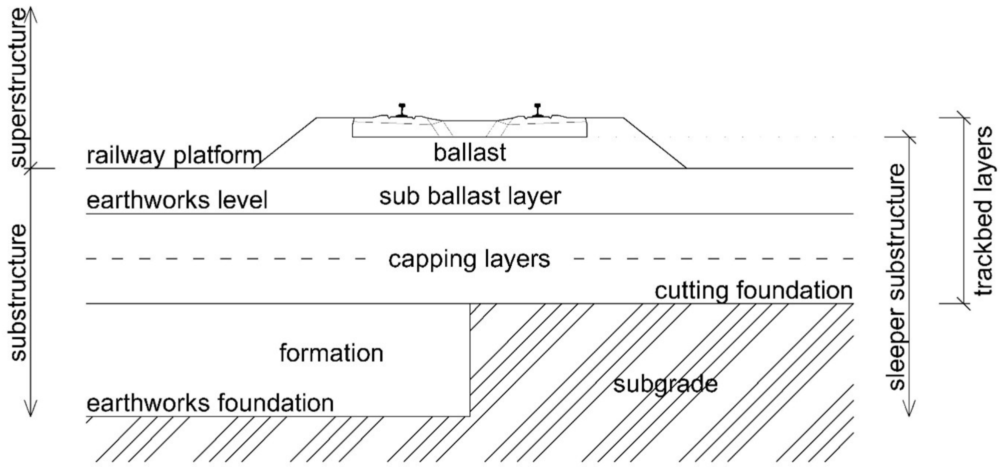

Figure 2. Sleeper substructure layers according to SŽ S4 [2].

Highest speed limit [kph]	Expected operational loads [millions gross tons/year]	Track class throughout whole lifetime	Composition of trackbed layers
≤80	<2	A – D	min. 200/ŠD 0/32 kv (min. 150 with the agreement of infrastructure manager)
	2–8	A – D	min. 250/ŠD 0/32 kv
	>8	A – D	min. 300/ŠD
81–120	<2	A – D	min. 250/ŠD 0/32 kv
	2–8	A – D	min. 300/ŠD 0/32 kv
	>8	A – D	min. 300/ŠD
121–160	<2	A – D	min. 300/ŠD 0/32 kv
	2–8	A – D	Var. I: min. 400/ŠD 0/32 kv Var. II: min. 250/ŠD 0/63 kv
	>8	A – D	Var. I: min. 400/ŠD 0/32 kv Var. II: min. 250/ŠD 0/63 kv
161–200 (incl.)	For all operational loads	A – D	Var. I: min. 400/ŠD 0/63 kv Var. II: min. 100/asphalt concrete + 250/ŠD 0/63 kv

Table 1. Design of the composition of sub-ballast layers of the SŽ S4 standard.

nels), the transition area is created using a reinforced sleeper substructure. This is done by designing a reinforcing layer (in other words, practically another capping layer) that increases the bearing capacity of the transition area and this layer is included in the calculation and design of the sleeper substructure.

The decision-making process for the design of transition areas is demonstrated using a flow diagram shown in Figure 3. It is apparent, that the process is excessively complex and that simplification should be proposed shortly to unify the substructure design of the railway tracks.

In our specific case for the main tracks the standard requires an increase in the static deformation modulus on the railway platform $E_{min,PL} = 100\,\mathrm{MPa}$. To achieve such a high value, we designed a capping layer of crushed aggregate mixed with cement under the sub-ballast layer, while other capping layers were designed of enhanced soil or crushed aggregate. For low-bearing clay, even 3 sub-layers had to be designed in the areas with reinforced sleeper substructures.

7. Design of Sleeper Substructure in Stations

In the next phase of the design, we dealt with the design of the sleeper substructure for the other tracks in the stations (apart from the main tracks). Track speeds ranged from 40 to 130 kph with the entire range of operating loads considered by the regulation. See Table 2 for the required deformation modulus for the earthworks level and the railway platform.

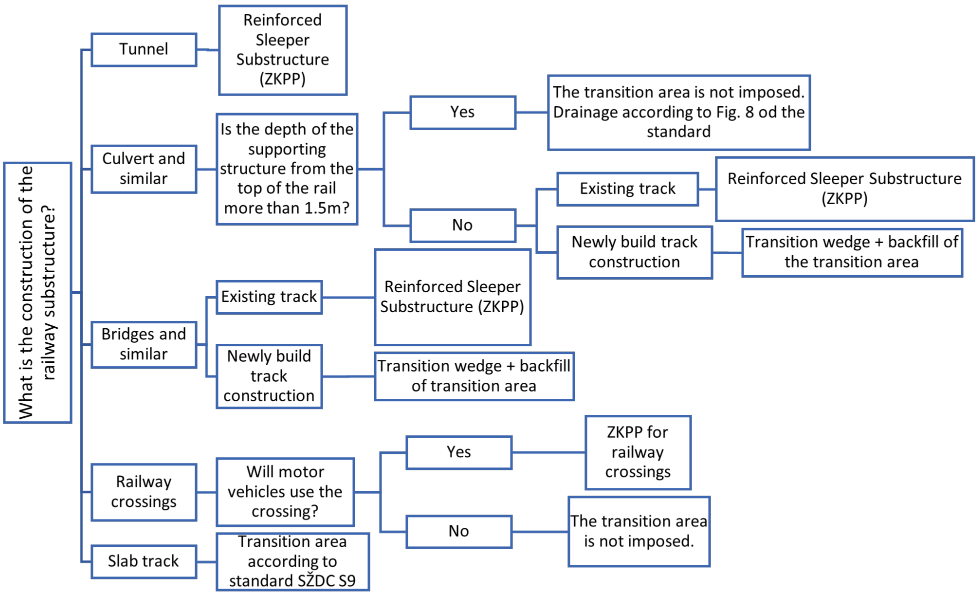

FIGURE 3. Flow chart for design of transition area.

Highest speed limit [kph]	**Expected operational loads [millions gross tons/year]**	**Track class throughout whole lifetime**	**The minimum required deformation modulus [MPa]**	
			$E_{min,ZP}$	$E_{min,PL}$
≤80	<2	A – D	15	30
	>2	A – D	20	40
81–120	<2	A – D	20	40
	2–8	A – D	30	50
	>8	A – D	30	50
121–160	<2	A – D	30	50
	2–8	A – D	40	60
	>8	A – D	40	60
161–200 (incl.)	For all operational loads	A – D	70	90

TABLE 2. The minimum required bearing capacity on the earthwork level $E_{min,ZP}$ and the railway platform $E_{min,PL}$.

Most of the objects of the railway substructure were located in the stations, so transition areas had to be designed for the other tracks in the stations as well. For these, the standard for new objects sets a minimum value of 80 MPa at the level of the railway platform.

As it turned out, in some cases it is not possible to solve according to the SŽ S4 standard. The problem originates in the fact, that the standard does not allow the use of crushed stone fraction 0/63 (ŠD 0/63 kv – see Table 1) for speeds up to 120 kph (inclusive). The fundamental difference in bearing capacity between fractions ŠD 0/32 kv and ŠD 0/63 kv is the deformation modulus: material ŠD 0/32 kv has a deformation modulus of 70 MPa, while ŠD 0/63 kv has a deformation modulus of 100 MPa. Therefore, when a static deformation modulus of 80 MPa is to be achieved, it is practically impossible with the material of the sub-ballast layer of 70 MPa. It is theoretically possible to oversize the capping layer to achieve this value, but this is a very inefficient solution (see Figure 4).

It is clear from Figure 4 that the required value of the static deformation modulus on the railway platform of 80 MPa with the sub-ballast layer ŠD 0/32 can only be achieved with great difficulty. Since the deformation modulus of ŠD 0/32 kv is lower than the required value of the static deformation modulus, it is not possible to achieve this value by increasing the thickness of the sub-ballast layer. In our model example, we achieved the desired value using the soil enhanced with a hydraulic road binder with a thickness of 1 m as a capping layer (in practice it would

Clay sand (S4 SM): Reduced static deformation modulus E_{0r} [MPa]	15
Track speed V [km/h]	120
Operating load [mil. hrt/year]	6
Required static deformation modulus on capping layer [MPa]	**30**
Required static deformation modulus on railway platform [MPa]	**80**

Capping layer:

Soil improved with hydraulic road binder

Deformation modulus E_{mat} [MPa]	110
Layer thickness [m]	0,4
The resulting value of the static deformation modulus on the capping layer [MPa]	**58,54**

Sub ballast layer:

Crushed stone fraction 0/63 (ŠD 0/63 kv)

Deformation modulus E_{mat} [MPa]	100
Layer thickness [m]	0,25
The resulting value of the static deformation modulus on the railway platform [MPa]	**80,09**

Capping layer:

Soil improved with hydraulic road binder

Deformation modulus E_{mat} [MPa]	110
Layer thickness [m]	**1,0**
The resulting value of the static deformation modulus on the capping layer [MPa]	**105,82**

Sub ballast layer:

Crushed stone fraction 0/32 (ŠD 0/32 kv)

Deformation modulus E_{mat} [MPa]	70
Layer thickness [m]	0,3
The resulting value of the static deformation modulus on the railway platform [MPa]	**80,98**

FIGURE 4. Samples of the design for the sub-ballast layer from the ŠD 0/32 kv and ŠD 0/63 kv.

be 2 capping layers with a thickness of 0.5 m). The uneconomical nature of such a design is demonstrated by the thickness of the capping layer, which is 2.5 times greater with ŠD 0/32 than with ŠD 0/63.

Due to the high count of transition areas in the stations and our effort to maximize homogenization of the sub-ballast layer, we proposed the usage of a sub-ballast layer of ŠD 0/63 kv in all tracks, even though the standard does not allow this option for lower speeds.

Another illogicality that we encountered during this step of the design can be found in Table 3 of Appendix 6 of the S4 standard (see Table 1) for a speed of 81–120 kph and an expected operating load greater than 8 hrt year^{-1}. In this case, the standard allows the use of the fraction 0/63, but at the same time, it prescribes a thickness of 300 mm for both ŠD 0/32 kv and ŠD 0/63 kv. However, for the same load and higher speed, the regulation allows the use of a thickness of only 250 mm in the case of ŠD 0/63 kv. It is therefore logical to use this thickness even for the lower speed.

8. Embankments

The design of the sleeper substructure in embankments requires information about the static deformation modulus. Standard S4 [2] in its current version only determines the suitability of soil for use in an earth body, but it does not include the indicative static deformation modulus. Therefore, it would be advisable to include the standard overview of the expected parameters of soil used for embankment construction and values of indicative static deformation modulus at the earthworks level in the same way as it is prescribed for original soil in cuttings.

In our case, after agreement with the investor, we assumed the enhancement of the used soil and thus the value of the static deformation modulus at the level of the earthworks level in all embankments is set to $E_{ZP} = 30$ MPa.

9. Conclusion

The S4 standard is a functional and comprehensive tool for the design of sleeper substructures. Its application to the design of the sleeper substructure of a long section of a newly constructed railway track at a speed of 200 kph showed several contexts that were not fine-tuned during the creation of the standard and which would be appropriate to incorporate into the standard in the future, in particular:

- include solutions for transition areas of tunnels in Appendix 24 (Transition areas);
- allow the use of a sub-ballast layer of ŠD 0/63 kv for all track speeds and loads, taking into account the high required static deformation modulus on the railway platform $E_{min,PL}$ at transition areas;
- for track speed of 81–120 kph and operational load greater than 8 million hrt year^{-1} allow a sub-ballast

layer thickness of 250 mm for ŠD 0/63 kv;

- add the value of the Deformation modulus for cement-enhanced soils to table 2 in Appendix 6;
- add values of the indicative static deformation modulus for soil used in the embankment;
- establish a clear design methodology of transition areas – procedure – flow diagram.

The experience with the design also shows the necessity of a quality geotechnical survey. In practice, we often encounter the fact that geotechnical surveys are not carried out at all for smaller constructions, while for larger constructions the investor does not carry out a sufficiently detailed geotechnical survey in an attempt to save money or for lack of time. It should be noted that the quality of the design of the sleeper substructure directly depends on the quality of the geotechnical survey. The financial resources spent on a sufficiently detailed and high-quality geotechnical survey will then be returned during the construction itself thanks to the accurate and non-oversized design of the sleeper substructure.

References

[1] V. Tomeček. Předběžný geotechnický a hydrogeologický průzkum. Souhrnná zpráva: Modernizace trati Brno – Přerov, I. etapa Blažovice – Nezamyslice. Brno, 2009.

[2] Správa železnic, s.o. Standard SŽ S4. Železniční spodek. Praha, 2021.