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Research Paper

Determination of Substructure and Sub-ballast Layer Thickness of High-Speed Railway

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ABSTRACT

The thickness of trackbed layers plays a crucial role in distributing train loads to ensure that stresses on the sub-ballast and substructure remain within acceptable limits. Vietnam is currently studying the construction of a high-speed railway (HSR) on the North-South axis, with two scenarios involving train axle loads of either 17 tons/axle or 22.5 tons/axle. This study focuses on determining the appropriate thickness for the sub-ballast and substructure layers to accommodate these axle loads. Using analytical methods, calculations were performed to determine optimal trackbed thickness. The results indicate that for an axle load of 17 tons, the substructure thickness should be approximately 1.75 m, while the sub-ballast layer should be around 0.27 m. In contrast, for axle load of 22.5 tons, the substructure thickness increases to about 1.94 m, and the sub-ballast layer thickness grows to approximately 0.36 m. These variations highlight the impact of axle load on trackbed design. The substructure layer's thickness is particularly important as it directly influences stress distribution throughout the trackbed. A well-designed trackbed ensures the structural integrity of the railway system, sufficient load-bearing capacity, and cost-effective construction. Proper determination of layer thickness is essential to balance performance, durability, and economic feasibility in high-speed railway infrastructure projects. This research provides a foundation for optimizing trackbed designs in Vietnam's high-speed railway scenarios, contributing to safer and more efficient railway operations.

1 Introduction

The sub-ballast is the layer situated between the subgrade and the ballast. Its primary role is to provide a separation between the ballast layer and the subgrade. It prevents ballast from penetrating the subgrade layer. The sub-ballast layer ensures drainage for the subgrade layer and reduces stress caused by wheel/rail interaction on the subgrade layer.

The substructure is a crucial component of the railwaybed, as it affects both the track's performance and the required maintenance. The settlement of railwaybed is affected by the structure of the substructure layer.

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There are many studies in the world that have studied trackbed. In 1996, Li et al. developed a design methodology for determining the thickness of railway track granular layers to prevent subgrade failures caused by repeated dynamic traffic loads [1]. In UIC 719 R [2], the design of track substructure can be considered as two separate subjects for new and existing lines. British Rail developed a method for designing track foundations in which the required ballast depth to prevent excessive subgrade deformation is determined based on laboratory repeated load tests and the expected traffic load [3]. The Network Rail code of practice provides recommendations for the thickness of railwaybed layers on the UK railway [4]. The West Japan Railway Company specifies the required depth of trackbed layers in its construction and maintenance standards for both commuter and Shinkansen lines [5, 6]. In this study, the authors present a method for determining the sub-ballast and substructure thickness for HSR with two types of load axles of 17 tons/axle and 22.5 tons/axle based on self-weight, dynamic stress and soil shear strength.

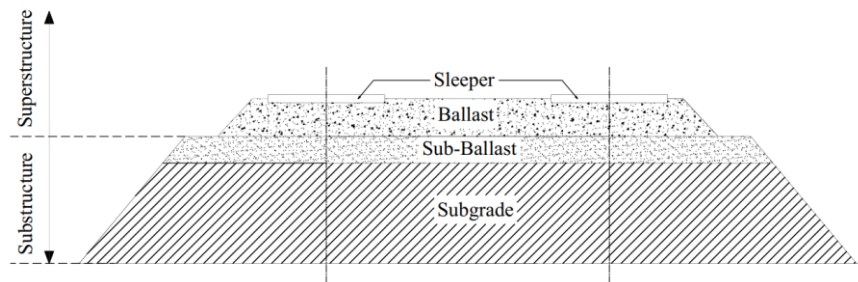


Fig. 1 – Schematic cross section

2 Theoretical Method to Determine Substructure and Sub-ballast

2.1 Load Distribution to Sleeper

The wheel load is transmitted from the rail to the pad and distributed to the sleeper such as the following Fig. 2.

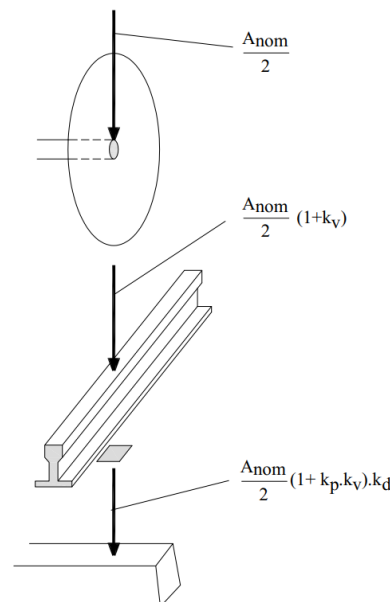


Fig. 2 – Load distribution to sleeper

The dynamic load value acting on the sleeper is calculated through the static load as follows [7]

$$P_k = \frac{A_{nom}}{2} (1 + k_p \cdot k_v) \cdot k_d \cdot k_r \quad (1)$$

where: A_{nom} : axle load of the vehicle

k_p : factor for rail pad attenuation

$k_p = 1$ for rail pads with low damping, characterized by attenuation of less than 15%;

$k_p = 0.89$ for rail pads with medium damping, characterized by attenuation of ranging from 15% to 30%;

$k_p = 0.78$ for rail pads with high damping, characterized by attenuation of greater than 30%.

k_v : factor for the effect of speed

$k_v = 0.25$ for speeds ranging from 0 to 60 km/h;

$k_v = 0.25 + \frac{v-60}{280}$ speeds between 60 and 200 km/h;

$k_v = 0.75$ for speeds of 200 km/h and above.

k_d : factor for longitudinal load distribution of sleepers

$$k_d = \frac{P_0}{Q_0}$$

Q_0 : unit wheel load, $Q_0=100$ kN;

P_0 : Load acting on the sleeper due to a unit wheel load Q_0 , $P_0 = c_{tot} \cdot \sum \eta_i y_0$ (N)

Stiffness for a single rail support, $c_{tot} = \frac{1}{\frac{1}{c_1} + \frac{1}{c_2}}$ (N/mm)

c_1 : the rail pad's stiffness under static loads (N/mm); c_2 : ballast and substructure stiffness (N/mm), $c_2=0.5 \cdot A_R \cdot C_2$ (N/mm);
 A_R : sleeper bearing area (mm²); C_2 : elasticity modulus for ballast and substructure (N/mm³);

y_0 : rail deflection caused by a unit wheel load Q_0 , $y_0 = \frac{Q_0 \cdot a}{2 \cdot c_{tot} \cdot L_{el}}$ (mm);

L_{el} : Winkler beam elastic length, $L_{el} = \sqrt[4]{\frac{4 \cdot E_R \cdot I_R}{c_{tot}/a}}$

E_R : the elasticity modulus of rail (N/mm²); I_R : the inertia moment of the rail (mm⁴); a : the distance of the sleepers (mm) and η_i : influence of the axle positions x_i :

$$\eta_i = \frac{\sin \zeta_i + \cos \zeta_i}{e^{\zeta_i}}$$

$$\zeta_i = \frac{x_i}{L_{el}}$$

k_r : factor that accounts for the longitudinal load distribution among sleepers caused by support faults, $k_r=1.35$.

2.2 Stress on Surface of Substructure

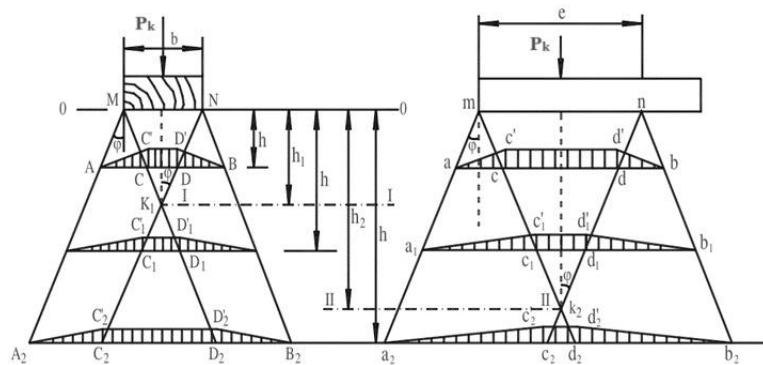


Fig. 3 – Stress transfer diagram in the substructure layer

Based on the intersection of the pressure diffusion lines K_1 , K_2 , we have h_1 and h_2 as follows

$$h_1 = \frac{b}{2} \cotg\varphi \quad (2)$$

$$h_2 = \frac{e}{2} \cotg\varphi \quad (3)$$

where: φ : pressure diffusion angle, $\varphi=35^\circ$; b : average width under the sleeper (mm) and e : effective support length of sleeper (mm)

- If $0 \leq h \leq h_1$: Stress in substructure

$$\sigma_h = m \frac{P_k}{b \cdot e} \quad (4)$$

m : non-uniform stress distribution coefficient

- If $h_1 \leq h \leq h_2$: Stress in substructure

$$\sigma_h = \frac{P_k}{2 \cdot h \cdot e \cdot \tg\varphi} \quad (5)$$

- If $h > h_2$: Stress in substructure

$$\sigma_h = \frac{P_k}{4 \cdot h^2 \cdot \tg^2\varphi} \quad (6)$$

2.3 Stress Due to Self-Weight

Formula for stress due to self-weight at depth z

$$\sigma_s = \sigma_{ss} + \gamma \cdot z \quad (7)$$

where : σ_s : self-weight stress at depth z ; σ_{ss} : superstructure's stress and γ : density of soil

2.4 Dynamic Stress

Formula for dynamic stress at depth z :

$$\sigma_z = \frac{2p_0}{\pi} \left[\frac{m \cdot n}{\sqrt{1+m^2+n^2}} \cdot \frac{1+m^2+n^2}{(1+n^2)(m^2+n^2)} + \arcsin \frac{m}{\sqrt{m^2+n^2} \cdot \sqrt{1+n^2}} \right] \quad (8)$$

where : σ_z : dynamic stress at depth z ; p_0 : stress at surface of substructure; $m = a/b$; $n = z/b$; $2a$: long side of the load and $2b$: short side of the load

2.5 Soil Shear Strength

Soil shear strength is determined such as following formula

$$\tau = \sigma \tg\varphi + c \quad (9)$$

where: σ : shear pressure of soil; φ : soil's angle of internal friction and c : soil's cohesion

3 Determining the Thickness of the Substructure and Sub-Ballast Layer for High-Speed Railways.

The substructure and sub-ballast layer thickness were calculated with the following input parameters: Two types of HSR train with axle load of 17t/axle and 22.5t/axle, speed 350km/h, rail 60E1, 1435mm gauge, sleep length 2.6m, soil density $\gamma = 17.5 \text{ kN/m}^3$, internal friction angle $\varphi = 52^\circ$, cohesion of soil $c = 80 \text{ kN/m}^2$.

Table 1 displays the values for static stress, dynamic stress, and shear strength.

Table 1 – Dynamic and static stress

No.	Depth (m)	Static stress (kN/m ²)	Dynamic stress (axle load 17t) (kN/m ²)	Dynamic stress (axle load 22.5t) (kN/m ²)	Shear Strength (kN/m ²)
1	0.0	5.22	157.21	208.07	86.68
2	0.1	6.97	145.91	193.12	88.92
3	0.2	8.72	113.91	150.76	91.16
4	0.3	10.47	85.38	113.00	93.40
5	0.4	12.22	64.94	85.95	95.64
6	0.5	13.97	50.53	66.88	97.88
7	0.6	15.72	40.17	53.16	100.12
8	0.7	17.47	32.53	43.05	102.36
9	0.8	19.22	26.77	35.43	104.60
10	0.9	20.97	22.34	29.57	106.84
11	1.0	22.72	18.88	24.99	109.08
12	1.1	24.47	16.14	21.36	111.32
13	1.2	26.22	13.93	18.43	113.56
14	1.3	27.97	12.13	16.05	115.80
15	1.4	29.72	10.65	14.09	118.04
16	1.5	31.47	9.41	12.46	120.28
17	1.6	33.22	8.37	11.08	122.52
18	1.7	34.97	7.50	9.92	124.76
19	1.8	36.72	6.75	8.93	127.00
20	1.9	38.47	6.10	8.08	129.24
21	2.0	40.22	5.54	7.34	131.48
22	2.1	41.97	5.06	6.69	133.72
23	2.2	43.72	4.63	6.13	135.96
24	2.3	45.47	4.26	5.63	138.20
25	2.4	47.22	3.92	5.19	140.44
26	2.5	48.97	3.63	4.80	142.68
27	2.6	50.72	3.37	4.45	144.92
28	2.7	52.47	3.13	4.14	147.16
29	2.8	54.22	2.92	3.86	149.40
30	2.9	55.97	2.73	3.61	151.64

When the dynamic stress is less than or equal to 1/5 of the static stress, the effect of dynamic stress on the substructure can be ignored [8]. Drawing a graph of static stress and dynamic stress on a coordinate system. The depth of the substructure layer is the distance from the point where the dynamic stress intersects with one-fifth of the static stress lines to the surface of the substructure.

Based on the chart in Fig. 4, we can determine the thickness of the substructure layer is 1.75m and 1.94m corresponding to the axle load of the HSR train is 17.0 tons/axle and 22.5 tons/axle.

Drawing a graph of dynamic stress and shear strength on a coordinate system. The depth from the surface of the substructure to the point where these lines intersect represents the location where the train's dynamic stress exceeds the soil's shear strength. This depth is the sub-ballast thickness.

According to the chart in Fig. 5, the thickness of the sub-ballast layer is determined to be 0.27 m for an axle load of 17.0 tons per axle and 0.36 m for an axle load of 22.5 tons per axle of the HSR train.

The research results are compared with the results of studies around the world and are consistent.

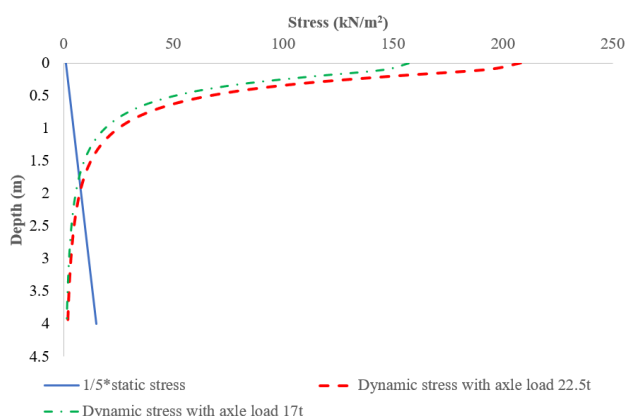


Fig. 4 – Chart of dynamic and 1/5*static stress

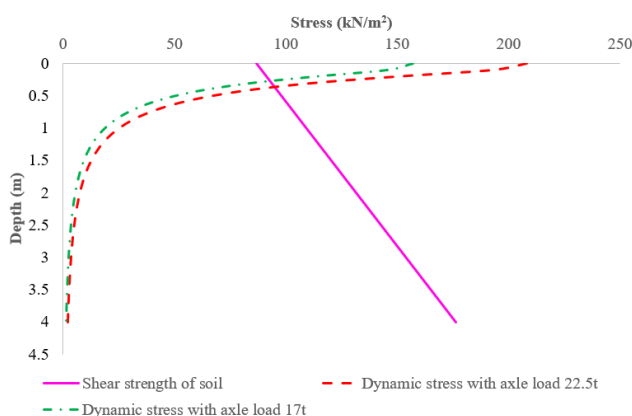


Fig. 5 – Chart of dynamic and shear strength

Table 2 – Comparison of the substructure thickness of present study and previous studies

No.	Country	Substructure thickness (m) [9]	Note
1	China	2.7	
2	Japan	≥ 3.0	
3	Germany	2.5	
4	Russia	2.5	
5	This study	1.75	Axle load 17.0t
		1.94	Axle load 22.5t

Table 3 – Comparison of the substructure thickness of present study and previous studies

No.	Country	Sub-ballast thickness (cm)	Note
1	France	20-55	
2	Germany	30-70	
3	Spain	25-30	
4	Italy	12	
5	Belgium	20-55	
6	United Kingdom	20-55	
7	This study	27	Axle load 17.0t
		36	Axle load 22.5t

4 Discussion

The trackbed is affected by the train's static and dynamic loads and simultaneously transmits and diffuses these loads to the foundation's depth.

Table 4 – Comparison of the substructure and sub-ballast thickness of HSR in this study and the conventional railway in Vietnam

No.	Thickness	Unit	HSR (axle load 17 t)	HSR (axle load 22.5 t)	Conventional railway [10]
1	Sub-ballast	cm	27	36	20
2	Substructure	cm	175	194	70

High-speed railways have very high requirements for treating the roadbed's subgrade and sub-ballast structure. The requirements and standards for filling materials, compaction, deformation control, and acceptance applied to high-speed railways are very different from those applied to conventional railways.

The calculation results show that the thickness of the sub-ballast and subgrade layer of the HSR are both larger than that of the conventional railway trackbed.

In addition, the calculation results are also similar to other studies in the world. The quality of the trackbed soil and the dynamic load of the train greatly affect the thickness of the trackbed layers.

5 Conclusions

The thickness of the substructure and sub-ballast layer provides stability for railway structures, facilitates smooth train operation, and lowers maintenance costs. The calculation results of sub-ballast and substructure layer thickness were performed with two types of HSR train loads. The thickness of the sub-ballast and substructure layers is influenced by the dynamic loads of the train. Train with axle load of 17 tons, sub-ballast and substructure thickness is 27 cm and 175cm respectively. Train with axle load of 22.5 tons, sub-ballast and sub-structure thickness is 36 cm and 194 cm respectively. The article introduces the method of determining the thickness of substructure and sub-ballast layer based on self-weight, dynamic stress and soil shear strength. The larger the dynamic load value of the train, the larger the thickness of the sub-ballast and substructure layers. The next research direction is to optimize the thickness of the railway trackbed layer to reduce construction costs.

REFERENCES

- [1]- D. Li, T.R. Sussmann, E.T. Selig, Procedure for railway track granular layer thickness determination. Association of American Railroads, Transportation Technology Center, 1996.
- [2]- UIC, Code 719R Earthworks and track bed for railway lines, in International Union of Railways Paris, France. (2008).
- [3]- D.L. Heath, J.M. Waters, M.J. Shenton, R.W. Sparrow, Design of conventional rail track foundations. Proceedings of the Institution of Civil Engineers, 51(2) (1972) 251-267. doi:10.1680/iicep.1972.5952.
- [4]- N. Rail, Company Code of Practice, Formation Treatments NR/SB/TRK/9039, 40 Melton Street, London W1 2EE. (2005).
- [5]- WJRC, Construction and maintenance standards for Shinkansen track. West Japan Railway Company, Osaka, (2002).
- [6]- WJRC, Construction and maintenance standards for commuter and local railway track. West Japan Railway Company, Osaka, (2002).
- [7]- BSI, EN 13230–6, Railway Applications. Track, Concrete Sleepers and Bearers, Part 6: Design, British Standard Institution (BSI) London, UK. (2020).
- [8]- H. Ying, Railway design. China: Southwest Jiaotong University, 1999.
- [9]- J. Fei, Y. Jie, C. Hong, C. Yang, Comparative analysis of design parameters for high-speed railway earthworks in different countries and a unified definition of embankment substructure. The Baltic journal of road and bridge engineering, 15(2) (2020) 127-144. doi:10.7250/bjrbe.2020-15.476.
- [10]- TCVN, 11793:2017, 1000mm gauge railway – Design requirements for track work, Ministry of Science and Technology Vietnam. (2017).