Railway Embankments on Soft Soil
a challenge for ageing infrastructure

1. Introduction

Switzerland underwent a rapid industrialisation in the 19th Century. The textile industry was booming, but it relied on a network of small roads to export production. Additionally, the country was facing social tensions between cities and the countryside, and of religious nature, resulting ultimately in a civil war (*Sonderbundskrieg*, November 1847). The arrival of the first French train in 1844 in Basel triggered an acceleration of the national railway projects. These were carried out by private enterprises and were seldom, unregulated and uncoordinated. The *Spanisch Brötli Bahn* connecting Zurich to Baden was the first railway to be inaugurated in August 1847, shortly before the civil war. Several other railways were then in construction. The second constitution of 1848 made the railway a federal matter (Act 1), and the government subsequently commissioned Robert Stephenson and Henry Swinburne, two well-respected British engineers, to plan the Swiss railways as a network in 1850. They proposed a 645-km network with two main axes, North-South and East-West intersecting in Olten. It excluded the Alpine routes because deemed technically unachievable then. They advocated for a single "standard" gauge to permit interoperable railways rather line-specific solutions, and this became compulsory in Switzerland for the next two decades. They recommended constructing railways along valley floors on flat terrain to diminish the construction length, the transportation time and, especially, decrease the amount of earthworks. However, flat terrain in mountains is often due to soft soil [1]. The recommendations became compulsory. The construction and operation of railways was left to private companies under cantonal supervision. The competition was big, and private railways were under financial pressure, but they nevertheless succeeded in building much of today's network (Figure 1).

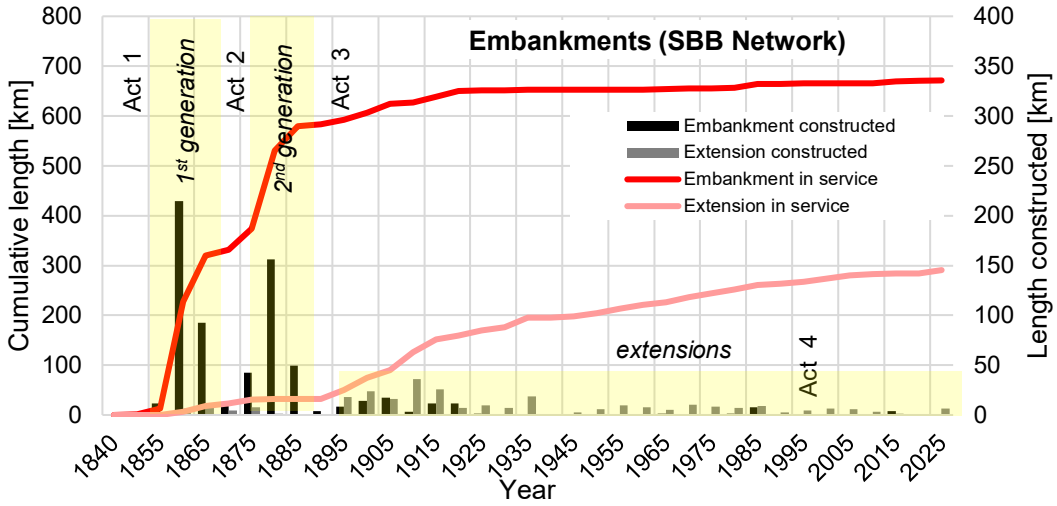


Figure 1: Construction of railway embankments at SBB.
Data from the "Fixed Installations Database" (Datenbank fester Anlagen = DfA) April 2026.

In 1870, the Swiss railway companies were struggling, and the federal government took over the control of construction, operations, tariffs and accounting (Act 2). There was also a military incentive to control railways and have an interconnected network. The reform now permitted narrow gauges, and some cantons favoured them to decrease earthworks and capital investment, but also to challenge national interests by not allowing standard-gauge trains to enter their region. The reform opened the path to nationalisation, and the Swiss Federal Railways (SBB) were founded in 1902 after a popular referendum (Act 3). It was missioned to make railways operate as a reliable, affordable, sustainable and self-reliant network. SBB made three major changes: (1) the network was extended to double track, (2) electrification was necessary to become self-sufficient and (3) railways were interconnected to form a network. Since then, SBB has become a public company (Act 4). Understanding how embankments were built and extended is paramount to understanding how they behave today.

2. The first generation of embankments (1850-1875)

Embankments were mostly constructed to level terrain offering a flat subgrade for the railway tracks. There is field evidence that some embankments were constructed to spread loads over soft grounds, and this contrasts

with the existing literature [2]. Earthworks were, and still are, very expensive, with a strong desire to minimise their numbers and size, and routes were chosen to balance out fillings with nearby cuttings. Some lines were built near, or even through, peat bogs to shorten routes but also to harvest the peat as a combustible. There was a desire to avoid villages because of social tensions between the countryside and cities. Figure 2 shows an embankment constructed in the 1850s in a peat bog away from villages and is still today in its original setup. The side borrows were then used to construct the embankment and then drain the site [3].



Figure 2: A railway embankment constructed in the 1850s using side cuttings. Photo credit: SBB (Fern) February 2026.

Many embankments were built during the “railway mania” of 1860-1890 and were constructed by hand with shovels and picks for soil and blasting techniques for rock. In some rare cases, steam engines were used; Skempton [2] reports 1 engine for 100 horses and 1,000 men in the UK, and it is unlikely to have been any different in Switzerland. The spoil was moved along the cuttings by horse-towed carts and tipped over at the end of the line, a technique known as “cut-and-fill”. The backfills sometimes originated from borrow pits. Side-cuttings were preferred and consisted of constructing ditches along the track and using the spoil as backfill, but this technique was twice the cost [2] as more land had to be purchased. Furthermore, the upper soil layers needed to be of relatively good quality to be used as backfill. Figure 2 shows a side cutting in its original state. Ground investigations using seismic piezocones (sCPTu) (Figure 3) confirm that the backfill originates from the cutting and consists of an organic sand with a lot of silts. It is unclear whether the upper 40cm of gravel (subgrade) is part of the original construction or was added later. Peat appears not to have been used for construction in Switzerland but was in other countries [5]. There was little attempt to prepare adequate foundations, and the topsoil was sometimes left in place (Figure 3). This made the construction cheaper and faster [5], albeit still slow. The progressive build-up of material compacted the ground, and the slow construction process allowed the subsoil to consolidate. The associated settlement was then compensated during the construction, and few contrasts in material (stiffness) are observed, unlike for the second generation of embankments. It also improved the subsoil. Consolidation increases density γ and, hence, the strength. The deadweight of the embankment increased the pressure and, thus, the stiffness. This can be seen with the shear wave velocity v_s measurements (Figure 3) because v_s is directly a function of density and pressure and increases between 4 and 10m for the same soil.

The George Stephenson, the father, developed a floating track system in 1830s. It consisted in placing a grid of brushwood bundles directly on the peat and topping it up with rubble stone to create a stable raft. The embankment could then be built. There is some evidence that such techniques were used in Switzerland as of the 1880s.

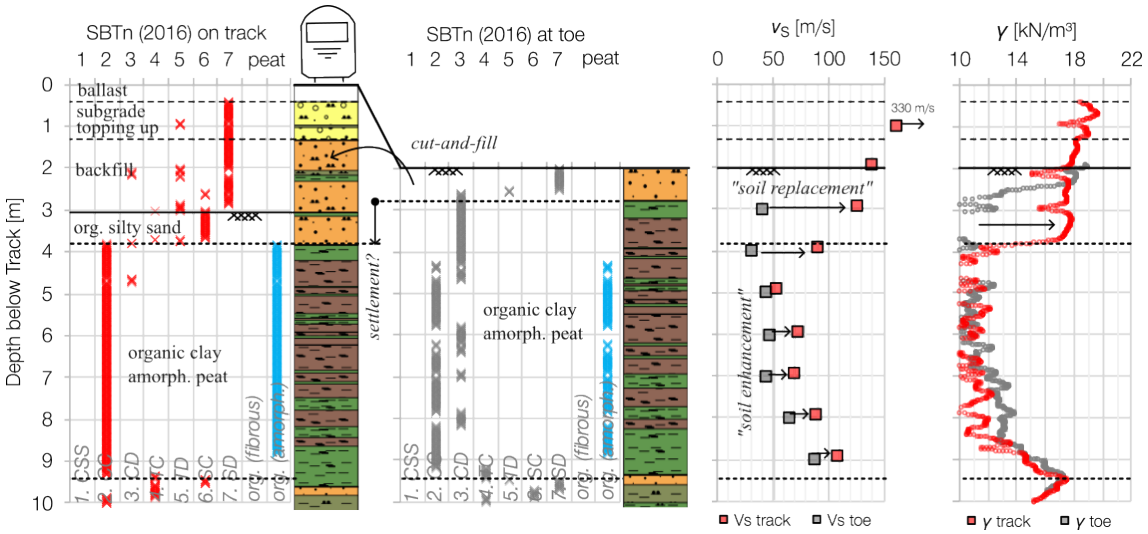


Figure 3: sCPT interpretation on and next to a first-generation embankment. Soil identification according to the normalised soil behaviour trend (SBTn).

3. The second generation of embankments (1875-1900)

Steam-powered construction machines were available by 1890 [5] and permitted moving larger quantities of material and the construction of large embankments, albeit previously achieved but at great expense. Whilst the first generation of embankments was constructed with locally available materials, the second generation was mostly constructed with silty sands and gravels, which are easier to process and construct with. Figure 4 shows the construction of a second-generation embankment. A temporary wooden viaduct was constructed at the desired height of the railway. Small wagons travelled back and forth from the cutting area (right side of photograph) and tipped the spoil sideways off the wooden structure (middle of photograph).



Figure 4: Construction of an embankment at Biglen BE in 1899 using side-tipping techniques. Source: Canton Bern Archives [reproduced with authorisation].

The large fall inferred great energy and compacted the soil upon impact, making the embankment stiffer and stronger, the fall height was often controlled and a contractual requirement. High rates of construction were achieved [2], and the construction duration was sometimes shorter than the consolidation time. The embankment and the track would later subside and then be corrected. The slopes were mostly larger than the angle of repose and were thus long-term unstable [1, 5]. Figure 5 shows the ground model of an embankment on soft soil constructed in the 1880s. The boreholes revealed the original embankment, which subsided, and the second one above it. The boreholes revealed a brushwood mattress at the base.

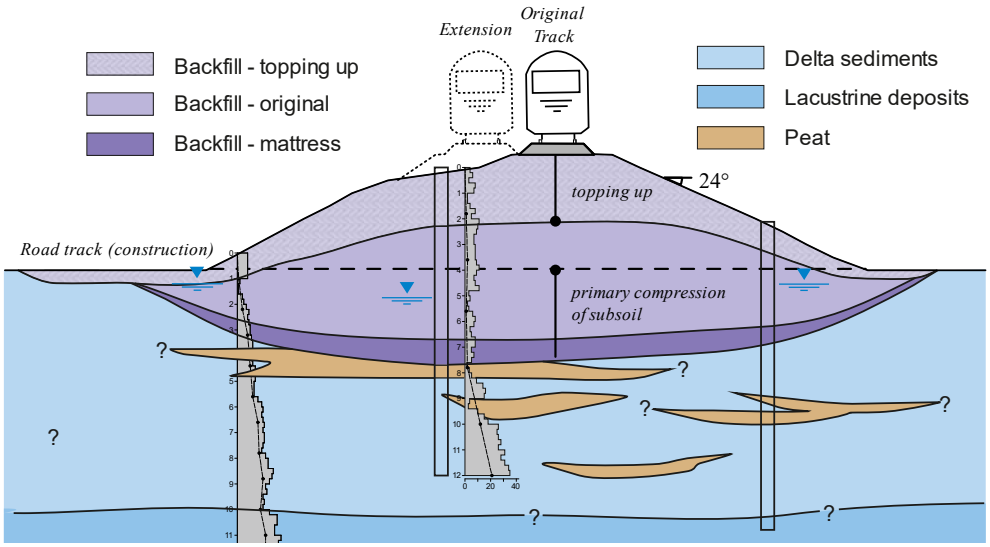


Figure 5: Ground model of a second-generation embankment on soft soil.

Figure 6 shows the interpretation of sCPTu on and next to this second-generation embankment. It appears that no peat is present below the embankments and it could have been removed voluntarily. This contrasts with the ground model (Figure 5) because it was determined using dynamic penetration tests only, and they do not distinguish peat from other loose and soft soils. A first embankment was identified and consists of locally available material. A second embankment was subsequently added using better quality materials, which were not locally available. The seismic wave velocities within the first two metres are, in this case extremely, low ($v_s < 50$ m/s) and suggests a very loose state. It is unlikely that the embankment was constructed as loose as this and it is an unusual state even for an old embankment. Hence, this state was caused recent disruption to the equilibrium of the embankment allowing to move or build-up excess pore water pressure induced by heavy traffic to become so loose. This state sets the track in a dynamic regime, which results in significant increase in rail deflection and plastic deformation known as embankment slumping [7]. This occurs when the train speed is close to the ground wave velocity ($v_{train}/v_{crit} > 0.625$ with $v_{crit} = v_R \approx 0.9\, v_s$).

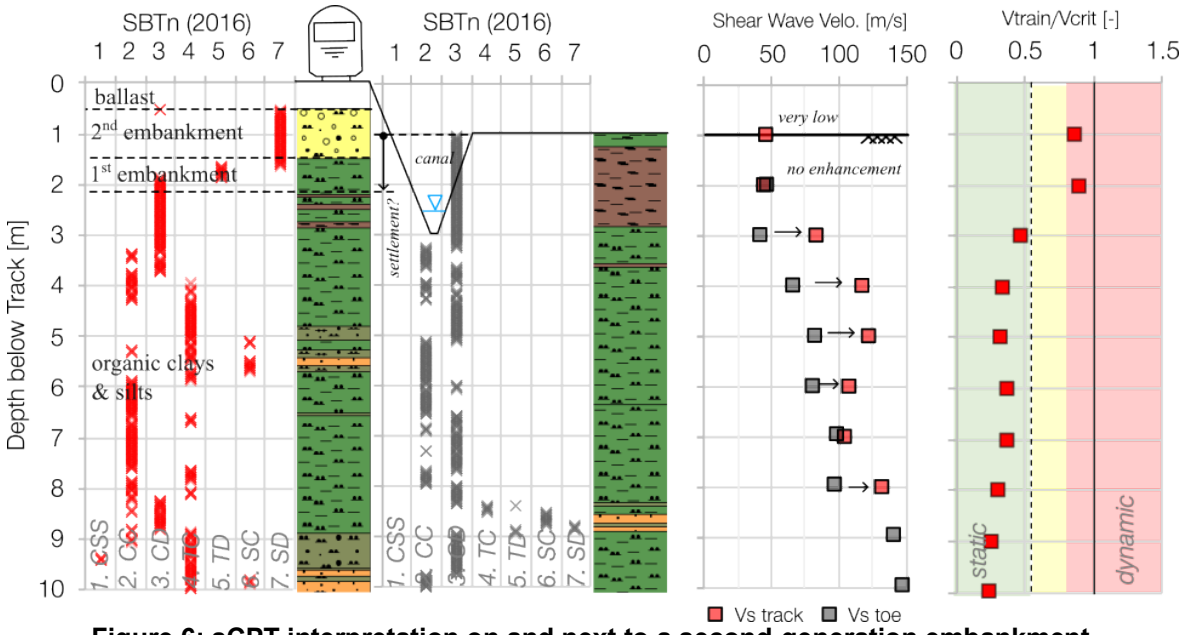


Figure 6: sCPT interpretation on and next to a second-generation embankment. Soil identification according to the normalised soil behaviour trend (SBTn).

Fern et al. [8] investigated the interaction between embankments and their subsoil by means of centrifuge testing and numerical analyses. It appears that the deformation mechanism depends on the contrasts in stiffness (Figure 7). Soft embankments on soft subsoil exhibit significant, progressive and diffused deformations. If the embankment had been initially dense, the deformation would have localised in shear bands, permitting piecewise rigid-body movements. The critical state [9] is then achieved within the shear bands [10]. The embankment has a heterogeneous distribution of density in addition to the material heterogeneity caused by the

construction techniques of the time. However, these tests were carried out on homogeneous embankments, which differ from old railway embankments. Computerised tomography (CT) scanning of railway embankments show a complex soil fabric and thus a complex mechanical behaviour [11].

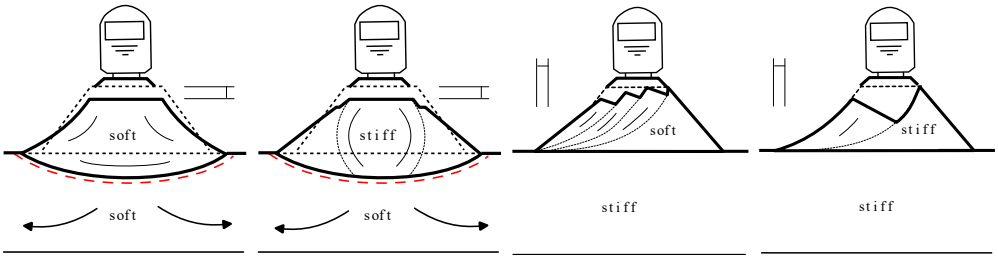


Figure 7: Deformation mechanisms of embankments on different subsoils.

Although it might seem at first that the lightly compacted embankments would relate to engineering deficiency, it has the advantage of letting the embankment deform progressively and find a metastable configuration with little softening. Additional backfill is then added to the embankment to achieve the desired elevation with little contrasts in stiffness. They then gain in strength and stiffness over time with the ageing effects and the railway traffic.

4. The extension of railway embankments (1900 onwards)

The Swiss railway network was extended to double tracks as of the 1900s and was mostly complete by the 1920s, though extensions are still ongoing today on regional lines. There is little published on how this was achieved. Most of the information presented in this paper is thus deduced from current observations on these embankments.

Materials were sorted and transported to the site over large distances, and new types of materials emerged. Construction and industrial waste, such as bricks and slag, were common in urban areas, and these are still often found in the embankments. The extension of embankments was carried out mostly by side-tipping from the existing track and then compacted in layers, inferring a contrast in stiffness between the newly built extension and the ageing embankment, and this contrast is stronger for the first generation of embankments than the second. Embankments were mostly extended on one side, inferring a differential loading of the subsoil and resulting in differential settlement. The resulting settlement (Figure 8) is thus differential and mostly compensated with additional ballast, slag and ash. Therefore, the current state of the embankment is highly heterogeneous, anisotropic and certainly not symmetrical.

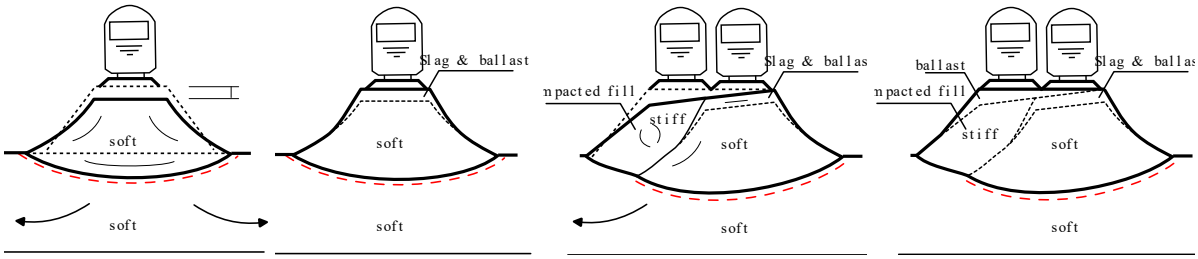


Figure 8: Illustrations of the history of deformation of embankments.

It is very difficult to know which track is the original track in absence of landmarks as such details were not recorded in maps and photographs were still scares. Many lines follow lakes and hills, and the extensions were built mostly outwards into the lake or the valley. The use of side tipping techniques from the existing track also implies that most embankments were extended on one side rather than both. Additionally, the track positions have been corrected over the time, and this increases the difficulties in identifying the original embankments in absence of detailed geotechnical investigations.

The double-track extension is ongoing. Switzerland is experiencing a rapid demographic growth, which in turn increases demand for railway transportation, but also expands urban areas and makes access to land difficult. The expansion of surrounding civil infrastructure, such as bridges, roads, utility services and buildings, constrains the railway to its original route and elevation, and it is therefore not possible today to move a line out of difficult ground conditions. These constraints favour other types of extensions with a smaller land footprint. However, the extension of the embankment is often possible in rural areas, and it follows the same principles

as in the past, but with significantly less construction time and keeping all tracks in service. The design of the extension must ensure minimal settlement and long-term stability of both the new extension and the existing tracks. The project must consider both the additional static deadweight and the one of the increased traffic as two trains can now stand on the embankment at a given moment. New construction follows modern design codes, and social expectations are higher. These constructions must be more robust and resilient than in the past. Among the biggest challenges is defining the design railway traffic load because it evolves over time, and it is not possible to determine what the traffic will be in 100 years, let alone financial constraints, which still put pressure on limiting investments to the strict minimum. Over-steep embankments are still customary today.

5. Modern challenges

Most railway embankments have been in service for over 150 years and will have to remain in service for the coming decades. They have reached the deterioration and unreliable phases, but the necessity to remediate will depend on the evolution of the performance and requirements (Figure 9). The requirements include transportation demands, which change paradigm every two decades, but also social expectations for the asset. Train availability and punctuality is probably the most important social expectation and puts significant constraints on the required asset performance. That means that the embankments need to construct with higher standards to meet tomorrow's needs.

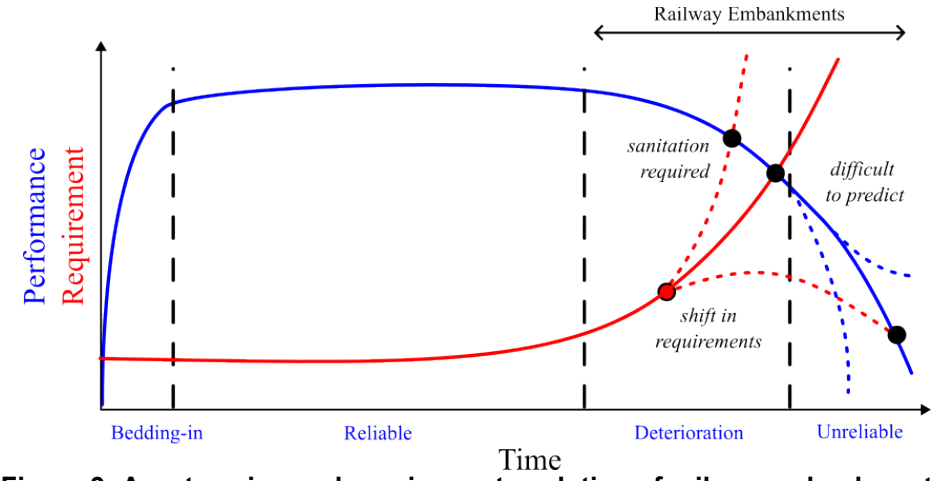


Figure 9: Asset ageing and requirement evolution of railway embankments.

The main challenge with ageing infrastructure is ensuring performance exceeds requirements over time. Sanitation work is planned when the prediction of requirements and performance match. The embankments were originally designed for steam engines and, as surprisingly as it may seem, their performance has been and is mostly adequate for modern traffic. However, some embankments constructed on, and sometimes with, soft soils are showing signs of limited performance, mostly relating to cyclic and dynamic deformation modes. Static behaviours due to the deadweight of the asset have mostly occurred during the early years. For instance, the Horgen train station was built on an extra-sensitive lacustrine soil, which collapsed in 1905 and slid into the lake some 20 years after the construction of the line. However, environmental changes can still induce additional primary compression. Record-low groundwater tables in recent years have increased the effective stress in the ground and have allowed embankments to settle. This is especially problematic for the first generation of embankments directly built on compressible soils such as peat. This is a major difference between ageing railway infrastructure and modern motorways, as the latter have been built much later in time. The impact of climate change on railway earthworks is discussed in detail in [6].

There are also other climate loads which impact embankments. The first generation of embankments is mostly constructed with locally available materials and can be prone to seasonal swell-shrink or frost-thaw phenomena, which progressively and over time decrease the stiffness of fine-grained soils. This results in the embankment slowly walking its way down the slopes [13]. The consequence of soil fatigue behaviours is the decrease of the ground wave velocity, and this can change the behaviour regime from quasi-static to dynamic. In extreme cases, the ground wave velocity is the same as the train speed. Energy is then accumulated under the train (resonance). There is only two ways to dissipate this energy. It can be returned to the train (elasticity) and can cause a derailment, or it is transformed into plastic deformation resulting in significant embankment damage. It was long believed that dynamic problems were only of concern for high-speed railways, but recent work [13, 14] shows that it is the relative train-to-ground speed which is determinant. Therefore, dynamic behaviours

can take place at low speed, e.g., 80 km/h, if the ground is sufficiently soft, and this has been observed in the network. Dynamic behaviours can easily be addressed with train speed reductions (TSR), albeit with consequences on the timetable. In addition to static and dynamic failure modes, soil fatigue can take place with the cyclic loading of the railway traffic. Although the magnitude of cyclic traffic load is smaller, the embankments have already experienced seven to ten million cycles, progressively decreasing the small-strain stiffness and, hence, the shear wave velocity of the ground. Swiss embankments tend to be silty, sandy and gravely. Coarse-grained materials consolidate faster and are easier to compact, but silt is sensitive to cyclic liquefaction, which was at the time of the construction irrelevant for steam engine traffic.

6. Closure

Railway embankments are ageing infrastructure. The first generation of embankments was built between 1850 and 1875 by hand and using locally available material. The second generation of embankments was constructed between 1875 and 1900 with steam-powered construction machines, which allowed moving and sorting material as well as compacting them. Since then, the embankments have been in continuous service, and many have been extended to double tracks since then. These extensions can be seen as the third generation of embankments with each generation having its own construction techniques resulting in different states. However, the railway network was initially constructed for steam engines. The railway traffic has since significantly increased in terms of train speed, train weight and number of train passages. Whilst most embankments perform adequately, some exhibit challenging dynamic behaviours. These are mostly embankments constructed on soft soil. To make matters worse, these tend to be on main lines, which are congested with limited closure time for repairs. This is not a coincidence because these lines were the first to have been constructed to connect the most important economic areas and the high traffic induces high loads and, hence, deformation.

Many challenges relate directly to the embankment design and construction process. The original network was not constructed by SBB but by private entrepreneurs. Capital investments were minimum and long-term performance was not a concern, allowing inadequate foundations and over-steep slopes. Moreover, it was only in the 2000s that the first inventory of earthworks was carried out using land surveying techniques, and many smaller fills have not yet been discovered. Additionally, the original constructions were poorly documented, and it is often not known whether the soft subsoil was removed, treated or left in place. It is thus necessary to carry out extensive geotechnical investigations for poorly performing embankments, but there is also a necessity to shift some old civil engineering paradigms to more modern performance-based ones. Asset ageing and unpredictability are part of the life cycle, but remediation work is not always necessary. The situation can be acceptable, provided that the requirements remain below the performance limit, and this is often the case for a regional line. This late stage in ageing implies that the asset managers need to develop tools and processes to react quickly as well as controlling the demand with respect to the performance, and this is exactly what many major railways, such as SBB, are currently doing.

References

[1] Geotechnik Schweiz, ‘Geotechnische Herausforderungen bei weichen Böden / Les défis géotechniques avec les sols mous’, Geotechnik Schweiz, Muttenz, Heft 181, 2022.
[2] A. Skempton, ‘Embankments and cuttings on the early railways’, *Constr. Hist.*, vol. 11, pp. 33–49, 1996.
[3] W. D. Haskoll, *Railway construction: from the setting out of the centre line to the completion of the works; containing instructions for ranging curves and setting out lines and levels in earthworks, permanent way, bridges & viaducts.* London: Atchley & co., 1857.
[4] J. Smethurst and W. Powrie, ‘Railway Earthworks: Design and Performance’, in *Sustainable Railway Engineering and Operations*, S. Blainey and J. Preston, Eds, Emerald Publishing Limited, 2022, pp. 91–111. doi: 10.1108/S2044-994120220000014006.
[5] W. J. M. Rankine, *A Manual of Civil Engineering*. London: Charles Griffin & Cie, 1862.
[6] R. J. Mair *et al.*, *A Review of Earthworks Management*. London: Network Rail, 2021.
[7] A. Duley, ‘Soil Parameters for Modelling Critical Velocity Effects of Railways’, Ph.D. Dissertation, University of Southampton, 2018.
[8] E. J. Fern, D. A. de Lange, C. Zwanenburg, J. A. M. Teunissen, A. Rohe, and K. Soga, ‘Experimental and numerical investigations of dyke failures involving soft materials’, *Eng Geol*, vol. 219, pp. 130–139, Mar. 2017, doi: 10.1016/j.enggeo.2016.07.006.
[9] K. H. Roscoe, A. N. Schofield, and C. P. Wroth, ‘On the yielding of soils’, *Géotechnique*, vol. 8, no. 1, pp. 22–53, Jan. 1958, doi: 10.1680/geot.1958.8.1.22.

[10] E. J. Fern, ‘Constitutive modelling of unsaturated sand and its application to large deformation modelling’, PhD Thesis, University of Cambridge, 2016.
[11] Mott MacDonald, ‘The effects of railway traffic on embankment stability’, London, RSSB 1386 (Revised), 2011.
[12] E. Recordon, ‘Remblais sur sols tourbeux ou craie lacustre’, *Bull. Tech. Suisse Romande*, vol. 98, no. 5, pp. 71–79, 1972, doi: 10.5169/SEALS-71536.
[13] M. D. Bolton and W. A. Take, ‘Seasonal ratcheting and softening in clay slopes, leading to first-time failure’, *Géotechnique*, vol. 61, no. 9, pp. 757–769, 2011, doi: 10.1680/geot.9.P.125.
[14] W. Powrie, ‘Railway track substructure: Recent research and future directions’, *Transp. Geotech.*, vol. 46, p. 101234, May 2024, doi: 10.1016/j.trgeo.2024.101234.
[15] P. Conay, P. Gilbert, A. Duley, and P. Fleming, ‘Pavement foundation design’, in *ICE Manual of Geotechnical Engineering, Second edition, Volume II: Geotechnical design, construction and verification*, 2nd edn, vol. 2, 2 vols, M. Brown, J. Burland, T. Chapman, K. Higgins, H. Skinner, and D. Toll, Eds, Leeds: Emerald Publishing Limited, 2024. doi: 10.1680/icemge.66830.1251.

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