Soft soils under the Swiss railway network

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Abstract. Switzerland is best known for its mountains and hard rock, but far less for its soft soils, despite being an integral part of glacial geology. The Swiss railway network was constructed in the 19th century following the recommendation to build the tracks on valley floors where soft soil is present. Whilst satisfactory back then, it is a challenge. The Swiss Federal Railways have approx. 15% of the network on soft soils, and these locations need to be regularly explored and verified. This paper explains how these soils can be identified and then illustrates several unusual cases found in the network.

1 Introduction

Although Switzerland is best known for its snowy mountains, soft soils are an intrinsic part of the country's glacial geology. The morphology of Switzerland has been shaped by Pleistocene glaciers and their retreat, filling valley floors with a variety of alluvium resulting from the abrasion of the glaciers on the bedrock, but, more importantly, creating lakes, floodplains and wetlands, where organic soils are formed.

Historically, most cities and villages were founded on good grounds such as rock, moraines and debris cones from adjacent mountains into the floodplains. Soft grounds and, especially, organic soils were used for agriculture. During the mid-19th century, Switzerland constructed the railway network following the recommendations of Robert Stephenson and Henry Swinburne. They suggested placing railways on valley floors where the terrain is flat terrain. However, flat terrain in mountainous areas is mostly composed of young soils from the Holocene epoch or glacial soils, which have been remoulded by glacial retreats during the late Pleistocene epoch.

Approx. 15% of the federal network is constructed on, and sometimes, with soft soil. Whilst this was satisfactory for steam engines, it is not always the case for modern railway traffic, which operates on the same lines. There are more trains today and they are longer, heavier and faster. Although the track bed has been renewed and upgraded several times, the subsoil and earthworks are mostly the original ones. Fig.1 shows different deformation patterns of the railway infrastructure. The Swiss Federal Railways (SBB) have developed network-scale verification techniques to identify potentially vulnerable soils for the track bed [1]. This paper presents several case studies and discusses special characteristics of soft alpine soils and how these are unidentified.

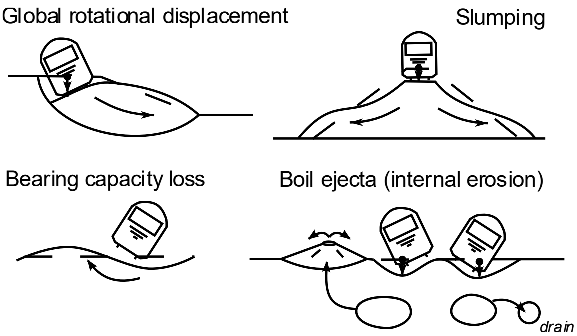

Fig. 1. Typical deformation patterns observed in the network.

2 Vulnerable soils and critical sites

2.1 Vulnerable soils

Vulnerable soils are those which can potentially undergo excessive, difficult-to-predict or uncontrolled deformation under conventional loading conditions; the term *soft* is not used because of its direct and specific reference to the stiffness, excluding many other soils. Hence, the substantial increase in railway traffic makes some soils vulnerable today that were not vulnerable at the time of construction. Additionally, the subsoil has evolved over the 175 years of service. Large-strain consolidation took place within the first years, compacting the ground and mostly enhancing its mechanical characteristics. Classical static failures due to the deadweight of the infrastructure have also mostly occurred. However, small-strain fatigue-like failures are emerging and are due to large number of train passes; Switzerland has the most congested railway network in the world. Dynamic effects caused by the train speed also take place and amplify the cyclic behaviours and become maximum when the train speed coincides with the ground wave velocity (resonance), and this can be the case with low train speeds with very soft soils, which

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have been left in place during the construction period of 1850 to 1880. Hence, the prevailing failure mechanisms differ between new and ageing railway infrastructure.

Whilst all civil engineers are educated in large-strain soil mechanics for civil structures, fewer are in small-strain soil dynamics, often excluding soil degradation from their analyses. Much of the science was initially developed for earthquake geotechnics [2,3], but many theories can be generalised to all cyclic problems [4] and must be considered when investigating old railways. Fig. 2 shows the different strain ranges for different industries and investigation methods.

SBB [1] reviewed the vulnerable soils and sites for medium-high speed railways by defining the critical failure mechanisms and post-failure behaviours. It was found that the shear wave velocity v_s was the best-suited field measurand because it relates directly to the small-strain shear stiffness G_0 given in Eq. (1) and the critical train speed v_train given in Eq. (2) [5].

$$G_0 = \rho {v_\mathrm{s}}^2 \tag{1}$$

where ρ is the soil unit mass.

$$v_\mathrm{train} = 0.625\ v_\mathrm{R} \approx 0.526\ v_\mathrm{s} \tag{2}$$

where v_R is the Rayleigh wave velocity ($v_\mathrm{R} \approx 0.9\ v_\mathrm{s}$).

Potentially vulnerable soils for medium-high speed railways typically have $v_\mathrm{s} \ll 140$ m/s, but mostly $v_\mathrm{s} < 115$ m/s [1], and relate to soil class E and F in the NEHRP classification system [1,6], albeit v_s alone is not sufficient to identify all vulnerable soils. These are mostly contractive to very contractive soils. However, the shear wave velocity is not a material property, because it is a function of the stress state, and it is the normalised shear wave velocity v_s1 which should be used as given in Eq. (3) [7].

$$v_\mathrm{s1} = v_\mathrm{s} \left(\frac{p_\mathrm{a}}{\sigma'_\mathrm{v}}\right)^{0.25} \tag{3}$$

where p_a is the atmospheric pressure and σ'_v the vertical effective stress.

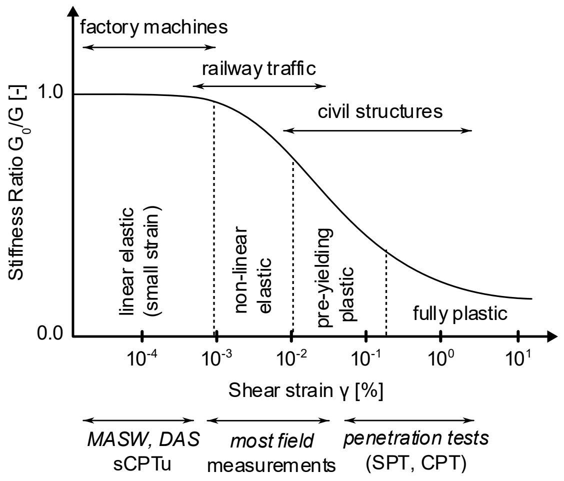

Fig. 2. Strain range for different infrastructure and investigation methods.

2.2 Critical sites

A site becomes critical when a soil unit is sufficiently soft to potentially induce rail misalignment. It is important to identify whether a site has potentially vulnerable soils, as complementary field investigations, geotechnical analyses and design work might be necessary. SBB developed a site classification system [1] to categorise sites and inform asset managers of engineering needs. It is based on an equivalent spring stiffness and relates to the track stiffness (Fig. 3). It is expressed in terms of an average shear wave velocity $v_{\mathrm{s}z_\mathrm{crit}}$ and given in Eq. (4).

$$v_{\mathrm{s}z_\mathrm{crit}} = \sum_{i=0}^{j|z=z_\mathrm{crit}} \frac{v_{\mathrm{s}i} d_i}{d_i} \tag{4}$$

where $v_{\mathrm{s}i}$ is the shear wave velocity for a given soil layer i, d_i its thickness and z_crit the critical depth.

The critical depth is typically 10m because most of the railway-induced cyclic loads are within this depth. However, it should be shortened if a stiff layer is accounted for within it. Whilst it relates to the NEHRP classification system [6], it was developed by considering the different failure mechanics of vulnerable soils to railway traffic. The classification is given in Table 1, and more information is given in [1].

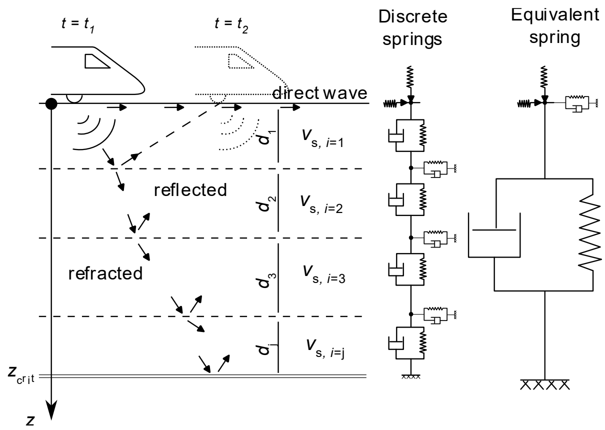

Fig. 3. Schematic representation of train-induced energy waves and modelling concepts.

Table 1. Railway geotechnical site classification after [1].

Class	v_s10 [m/s]	v_s30[m/s]	c_u [kPa]
A	>1100	> 1500	
B	575 – 1100	760 – 1500	> 100
C	280 – 575	360 – 760	
D	140 – 280	180 – 360	40 – 100
E	115 – 140	145 – 180	20 - 40
	or high-plasticity ($I_\mathrm{p} > 20\%$), loose ($I_\mathrm{c} < 0.5$, $I_\mathrm{D} < 35\%$), weak ($c_\mathrm{u} < 40$ kPa) or organic ($2\% < OC < 20\%$) soils with a thickness $d_i > 0.5$ m within 10 m depth.		
F	< 115	< 145	< 20
	or liquefied/liquefiable, with a strong microstructure, very sensitive ($S_\mathrm{t} > 8$), very organic ($OC > 20\%$) or very weak ($c_\mathrm{u} < 20$ kPa) soils with thickness $d_\mathrm{i} > 0.5$ m within 10 m depth, or Class E with thickness $d_i > 8$ m, or with $v_\mathrm{train} > 0.62\ v_R$) over $d_i > 0.5$ m.		

2.3 Field investigation

Small-strain characteristics can be assessed with ground (seismic) wave velocities using a wide range of measuring techniques, but not all vulnerable soils can be identified this way. This is the case for natural soils with strong inter-granular bonds, which have significantly higher small-strain stiffness than large-strain. This makes the seismic cone penetration tests (sCPTu) the most efficient and cost-effective exploration technique because it can assess both states in a single test at a given location. It becomes even more efficient when coupled with specific-depth sampling techniques. It is thus possible to identify critical soil layers by colour coding points with depth and determine whether a site is critical with CPT data, albeit in conjunction with other charts [8] and adequate laboratory testing. Note that it is customary to explore the subsoil alongside the track for operational and safety reasons.

Other techniques can also be used depending on the scale of the project. For instance, distributed acoustic sensing (DAS) is used to estimate the wave velocities for large projects covering tens of kilometres, if not hundreds. It permits defining critical regions and concentrating the limited means of investigations on these sites.

3 Case studies

Several case studies of railways on soft soils are presented in this section. The investigation techniques, laboratory testing and data processing are not discussed in this paper.

3.1 Tracks on peat

It is well known that Northern countries have extensive peat bogs, but wetlands are an intrinsic part of glacial geology. Switzerland had several very large glaciers, which formed large valleys and were filled with Holocene soils with complex layering systems, such as shown in Fig. 4. Most glacial lakes have a wetland at their entrance point, following the direction of the glacial flow. The type of soil formed depends on the hydraulic behaviour of the river, the lake and the evolution of the wetland. Alpine peat tends to have more minerals than conventional peat. This is because of the continuous erosion of the Alps, which provides minerals in the floodplains, and they get locked within the fibres. It is thus rare to have very high organic contents.

The railway was built in the early 1850s by end-tipping without any compaction. The construction was slow, which allowed the peat to consolidate, and the induced settlement was compensated for during the construction time. The backfill originated from the construction of a tunnel at km +0.0, and the slow construction process allowed the peat to consolidate under the embankment. The opening of the railway permitted the exploitation of the peat as combustible. This induced severe perturbation to the state of the subsoil with the overall drainage of the site and several open quarries. However, the line was single track, and it was only in 1920 that the second track was built. By then, more advanced construction techniques and machines existed. It is, however, unclear how this was achieved and what kind of backfill was used. In some areas, peat has also been used as frost protection within the railway subgrade, and this is problematic today.

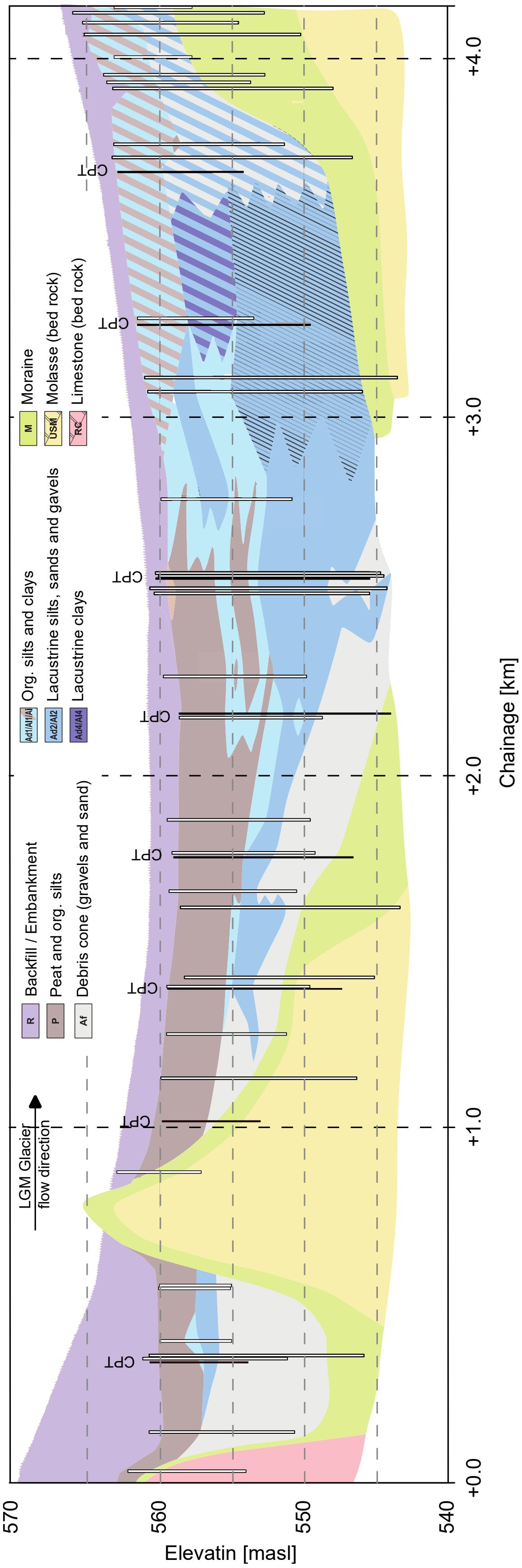

Fig. 4. Geological profile of Alpine floodplain with wetlands.

The subsoil was first investigated using conventional borehole explorations and (s)CPT. For cost reasons, only 1 out of 3 CPTs is seismic. The soundings were carried out at the embankment toe for safety reasons, and the analysis thus assumes that these earth structures are in a satisfactory state.

The CPT at chainage km +2.5 is illustrative of the geological conditions because it is located at the transition of the peat deposits and the soft lacustrine ones. The SBTn chart (Fig. 5) shows a dilative clay-like upper layer followed by contractive clay-like insensitive and sensitive layers. Finally, a stiffer dilative sand-like layer is encountered around 8.5m below the track. The analysis of the CPT parameters R_f and B_q suggest a thin layer of young fibrous peat at 4m, followed by 2m thick amorphous peat. Fig. 6 illustrates the two types of peat - a fibrous peat $LOI = 90\%$, $w_L = 335\%$ and $I_p = 121\%$, and the amorphous peat with $LOI = 65\%$, $w_L = 220\%$ and $I_p = 85\%$.

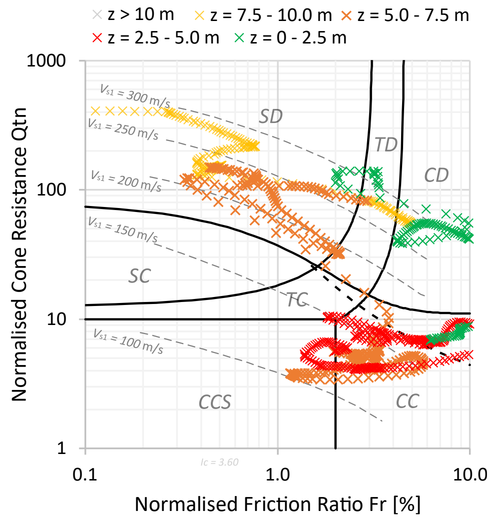

Fig. 5. SBTn chart at chainage km +2.5.

(a) (b)

Fig. 6. The two types of peat – fibrous (a) and amorphous (b). Photo credit: Geotest 2023.

The CPT results suggest the existence of sensitive soils between 9 and 10m below the track, with a sensitivity of $S_\mathrm{t} \approx. 8$ with an undrained shear strength of $c_u = 15$ kPa. The borehole exploration confirmed a layer of lake chalk, a sensitive lacustrine soil with calcium soil structure. Laboratory testing gave $LOI = 18\%$, $w_\mathrm{L} = 80\%$, $I_p = 5.4$ and $m_{\mathrm{CaCO_3}} = 44\%$.

The SBTn plots the normalised shear wave velocities v_{s1} in the range of 100 to 150 m/s. These were also estimated using well-established correlations [10] and shown in Fig. 7. It is known that this v_s is a lower bound, but it is satisfactory for first-order assessment of railway subsoil conditions. The v_{s10} values range from 115 to 206 m/s, but the critical depth should be shortened to approx. 8.50, where a stiffer layer exists, but relates to the sensitive lake chalk. Nevertheless, the site falls in Class F because of the presence of peat and sensitive soils. The railway subsoil must be verified for dynamic, cyclic and static failures. The dynamic failures relate directly to the Rayleigh wave velocity and the train speed following the work of [5,11,12]. Fig. 7 shows the velocity profile and suggests mostly a pseudo-static behaviour of the ground. Although dynamic behaviours of railway tracks are better known for high speeds, they can become critical for medium-high speed railways with soft soils. Dynamic failures of the subsoil result in significant deformation of the track bed and, hence, high maintenance and cost. It can also result in train derailment in extreme cases.

The cyclic behaviour of the track bed is difficult to assess, but very important because railway traffic is quintessentially a small-strain problem of low magnitude but infinite cycles. Conventional cyclic element testing in the laboratory is not possible for railways, which are a low-cost infrastructure per unit length. However, it is possible to estimate a lower-bound cyclic resistance ratio CRR [13] and assuming $\gamma_{\mathrm{th}} = 10^{-4}$, which is very conservative because high-plasticity soils and peat have a significantly higher threshold [14–16]. The cyclic stress ratio CSR was obtained by means of numerical analyses. Fig. 7 shows that the cyclic loads can be taken over by the subsoil. This is due to the presence of the embankment, which is subjected to very high cyclic stresses.

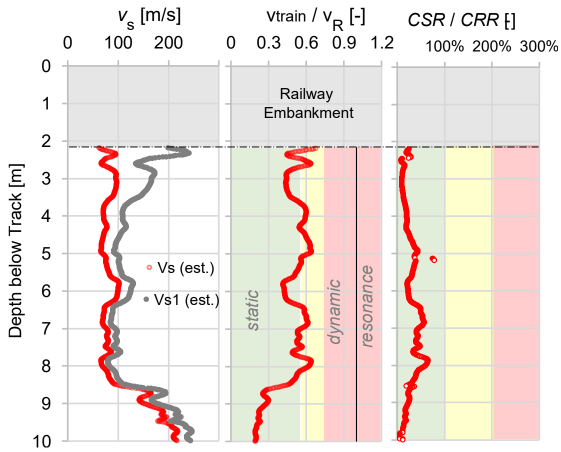

Fig. 7. Shear wave velocities and cyclic strength at km +2.5.

As pointed out by Powrie [5], static can alone be problematic. The CPT predicted static rail deflection can be calculated by considering the axle load and the estimated stiffness of the ground. This gives 3.9 mm in the present case but neglects any contribution of the railway subgrade, and compares well with the measured value of 3.3 mm. These values are acceptable but are in the higher range. A mismatch between the CPT-estimated and measured static rail deflection is often observed and is due to the contribution of the track bed and embankment.

Distributed acoustic sensing (DAS) was used with the existing telecommunication cables to map the state of the embankment and its subsoil following the work of [17]. The results suggest that the peat is sufficiently compacted to achieve sufficiently high shear wave velocities. MASW was also carried out at the embankment toe to verify the DAS results, and it shows heterogeneous lenses of peat with different shear wave velocities ranging from 98 to 165 m/s at km +0.5, but as low as 81 m/s at km +2.5. However, DAS struggles to characterise the first two metres of subsoil because very small gauge lengths are required and are technologically difficult to achieve. It also cannot identify sensitive soils because these have higher wave velocities when undisturbed than remoulded.

The analysis suggests the soft soil present under the track bed is satisfactory for the current railway traffic. During the summers of 2023 and 2024, the track underwent significant deformation and required significant maintenance. It is believed that the groundwater level dropped to a record low, and primary consolidation took place. These are climate-change-induced damages.

The assumption that embankments do not contain organic soils does not always hold true. Some were built by Robert Robertson using the Chat Moss (UK), which permitted crossing wetlands and decreasing the cost of construction. It consisted of placing a grid of brushwood directly on the ground and building the embankment directly on top of it. When no backfill was available, drainage ditches were dug on both sides of the railway, and the spoil was used as backfill. Whilst peat was mostly avoided, soft organic soils have been found in the track bed exploration pits.

The stratigraphy can also differ from conventional cases, as several peat deposits can be found at different depths. Landslides took place on the adjacent mountains, and debris cones can cover existing peat deposits before new ones are formed above them. This can also take place with the displacement of rivers in floodplains.

3.2 Tracks on Gyttja and Dy

Peat is the most well-known organic soil, but many other types exist. Dy and gyttja were found in one location under the railway network, although these were documented as "mushy silty peat". The distinction between both types of soil is paramount because their prevailing failure mechanisms are different. Peat is sensitive to primary consolidation, which has already taken place for existing tracks, but gyttja is sensitive to cyclic liquefaction. These result in different track deformation. Fig. 8 shows a boil in gyttja, and it is filled with dy and groundwater; no precipitation took place in the weeks before inspection. The segregation of the dy from the gyttja is caused by cyclic liquefaction and internal erosion. Organic matter has a small unit weight and can be fine-grained. It is thus the first to be in motion. The track drainage system was first filled with the material until it clogged. The flow then changed from the horizontal direction to vertical because the lateral boundary conditions became impervious, and excess pore pressure could only be dissipated at the ground surface.

The subsoil was explored by means of sCPTs and boreholes directly from the track and not next to the track for safety reasons (Fig. 9). The subsoil was so soft that sampling was difficult. Conventional samplers could not catch the sample because the soil flew out of it immediately. The sCPT results show that the moraine, a stiff glacial soil, was present at 3m depth. Hence, borehole tubes were pushed slowly down to this depth and plugged with the moraine, which worked well, but the tube friction was sufficient to prevent soil from penetrating into it, limiting the core recovery. Although the borehole core was not representative of the stratigraphy, it was possible to sample the ground and carry out laboratory testing (Table 2).

(a) (b)

Fig. 8. Boil (left) and railway subgrade and subsoil (right).

Fig. 9. CPT mounted on a railway wagon.

Table 2. Soil parameters at the site.

Parameter	Gyttja	Dy	Peat
Water content w [%]	25.7	255	54.1*
Specific gravity G_s [-]	2.69	2.04	1.28
Void ratio e [-]	0.93	5.2	-
Loss on ignition LOI [%]	2.9	40.8	71.7
Liquid limit w_L [%]	23.0	125	262
Plastic index I_P [%]	4.6	2.0	92
Calcium m_{CaCO_3}[%]	16.0	-	-
Compression index c_c [-]	0.169	2.257	-
Swelling index c_s [-]	0.014	0.332	-
Hydraulic conduct. k [m/s]	$5 \cdot 10^{-9}$	$1 \cdot 10^{-9}$	-

* not saturated.

Four types of soil units were identified: (1) gyttja-bearing sandy silt, (2) dy, (3) sphagnum peat and (4) the moraine. The three organic soils exhibit different mechanical characteristics (Table 2). The dy is not found in a pure form, but it is interbedded in the gyttja-bearing silt with a stronger concentration in the upper layers. The sphagnum peat is found above the gyttja-dy, and the moraine below it. The stratigraphy of the site was determined with the sCPTu. Fig. 10 shows the profiles next to the boil. The measured v_s values (red markers) clearly show the soil layers. The first value at 1m depth is 197 m/s within the track bed. It then drops to 90 m/s at 1.50m and, furthermore, to 55 m/s at 3m (gyttja) before significantly increasing to >300 m/s (moraine), showing the soft layer. The v_{s1} profile shows a higher contrast in values between the soft and stiff layers and is a better proxy for soil characteristics because it is independent of the stress state. The CPT-estimated v_s profile (red line) is also shown, but caution is required because the correlations might not hold true for the gyttja and dy. The comparison between the measured and estimated values suggests that the soil structure of the gyttja is unusually destructed and this is often observed in near-to-liquified soils. The dynamic verification ($v_{\mathrm{train}}/v_{\mathrm{R}}$) suggests that the ground behaviour is static, but the wave velocities are low, making the ratio very sensitive.

The estimated cyclic strength ratio (CSR/CRR) is high because CRR is low, partly because the gyttja has already undergone cyclic liquefaction with $G_0 \rightarrow 0$.

The SBTn profile clearly shows the different soil units, though the gyttja maps just within the clay-like dilative zone, despite having a small v_s. This is common for soils with unusual soil structures; the sensitivity estimation suggests an $S_t \approx 7$. The profile shows only 1 point (or 1cm) with $|R_f| > 4\%$ & $CD < 70$, typical of fibrous peat (blue cross in Fig. 10), but with an approx. 30% organic content. This contrasts strongly with the borehole log description, which suggests a peaty silt because of the brown colour and organic matter, highlighting how visual inspections alone can be misleading. The organic content was estimated according to [18] and is used as an indicator for organic soil when $|R_f| < 4\%$. The estimation suggests that the gyttja is very organic, which is the case.

The low plasticity and hydraulic conductivity of the soil make it very sensitive to liquefaction. Cyclic liquefaction is a fatigue-like failure, which differs from flow liquefaction by a metastable structure upon load removal. This failure mechanism is a direct consequence of heavy traffic; the cumulated traffic load of the track is 60,000 tons/day, which is a lot for a train speed of 80 km/h. It is, hence, a good example of the vulnerability of ageing tracks with modern traffic because no such phenomenon took place within the past 175 years of service. It is believed that the constructed railway drainage system, instead of improving the situation, aggravated it by creating a nil pressure point, increasing the hydraulic gradient and internal erosion. Tamping activity (vibro-compaction of the ballast) to correct the position of the track also accelerated the process.

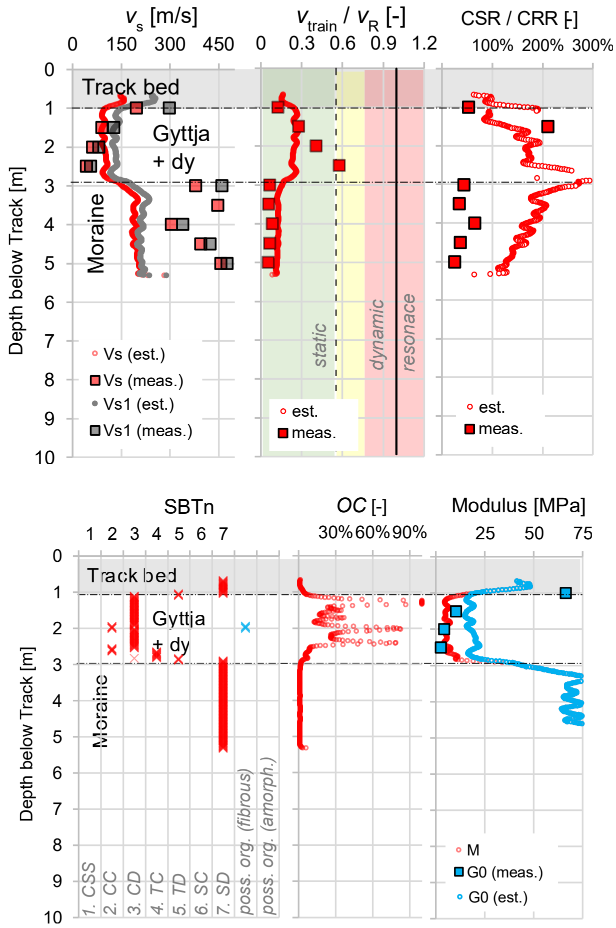

Fig. 10. CPT data of gyttja-bearing soil next to the boil.

3.3 Tracks on extra-sensitive soils

Northern countries are known to have quick clay, a glacial marine soil. However, alpine countries have a glacial lacustrine soil called lake chalk because it can have a high concentration of calcium hydroxide. It differs from quick clay by the absence of salt, which deactivates the clay, and a more abundant silt fraction. All lakes in Switzerland have some lake chalk, usually more abundant on the side of the lake than in its deeper parts. These soils can collapse and undergo flow liquefaction. This was the case in 1875 in Horgen when the railway and train station were destroyed by a landslide, albeit not triggered by the railway traffic.

Fig. 11 shows the CPT results in an extra-sensitive lacustrine soil at a nearby railway station. The v_s are around 100 m/s down to 16m, and the sensitivity $S_t = c_u/c_{res}$ ranges between 10 and 25. These high numbers are due to a very small residual undrained strength c_{res}, and caution is required when processing such data.

However, several CPTs in the area confirm extra-sensitive soils as well as laboratory testing [19].

It is known that a small amount of organic content facilitates the formation of open soil structures [20]. The organic content was estimated at 10% according to [18]. A borehole was undertaken using gel-push techniques, and samples were subjected to laboratory tests. They confirmed a shear modulus $G = 3$ to 6 MPa at 5m depth, as well as the sensitivity.

The mean velocity was found to be $v_{s10} = 96$ m/s, but estimated at 57 m/s. Both put the site in class F. It is really the strong microstructure (sensitivity), which justifies the class F and explains the difference in wave velocities.

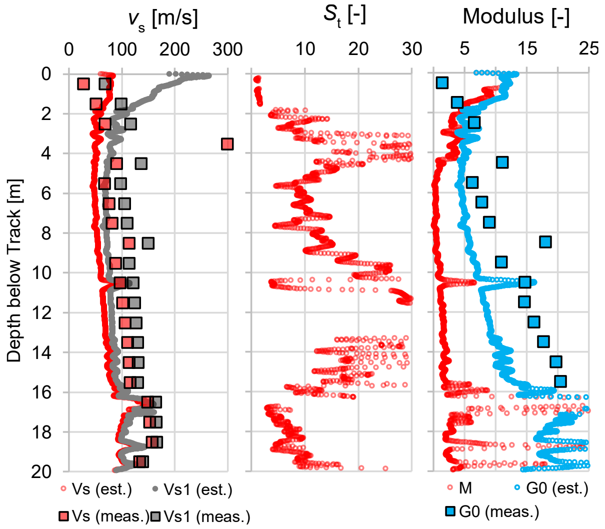

Fig. 11. CPT data of extra-sensitive lacustrine soil.

3.4 Tracks on liquifiable/liquified soils

Soft soils can also be found in the mountains. Fig. 12 shows a soft soil deposit in a lateral valley in the Alps. The shear wave velocities are very low, $v_s \ll 115$ m/s. Hence, the soil is soft with $G_0 \approx 5$ MPa - an abnormally low small-strain stiffness and $K_G^* \ll 300$ for typical Holocene soils. This exact location benefits from the presence of an embankment, which protects the subsoil from the dynamic and cyclic failures, but the subsoil suffers from continuous deformation, possibly secondary consolidation or critical state flow due to the deadweight of the embankment. Additionally, the embankment suffers from slumping, and the track needs regular correction. Structural damage is observed in the train station. Because the embankment is often smaller than shown in Fig. 12 and the subsoil is less protected, the traffic was slowed to avoid dynamic amplification.

Boreholes were carried out, and the soil was tested in the laboratory. The results show the presence of organic clay and silt with variable amounts of sand. The loss on ignition is $LOI = 6.7\% \pm 0.10$ with $w_L = 31.4\% \pm 10.6\%$, $I_p = 9.6\% \pm 5.5\%$ and $I_c = -0.52 \pm 1.09$. This implies that approx. 50% of the volume is water. The undrained shear strength is estimated at $c_u < 25$ kPa, and the first 7m appear insensitive. The mean velocity was found to be $v_{s10} = 111$ m/s, but estimated at 123 m/s. Both classify the site as F. Whilst it is common to have high-perched soft spots, it is not common to find deep soft soil deposits at altitude. The extraordinarily loose state could be due to important groundwater seepage in the valley. It is also possible that the upper section of the soil is a landslide debris cone, explaining the unusual unstructured state of the soil, followed by similar soil with a stronger fabric.

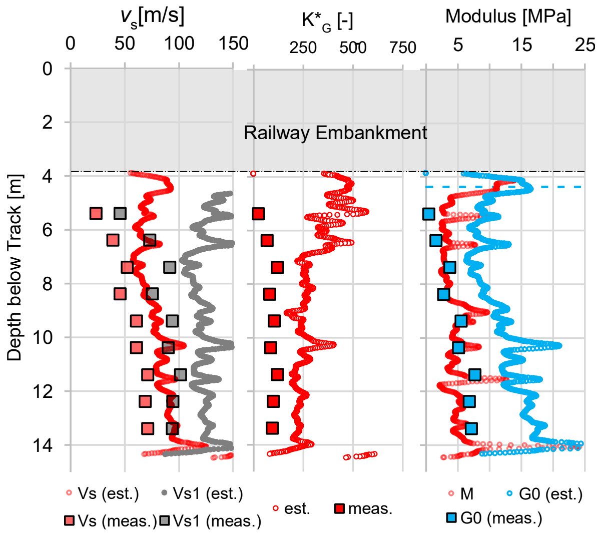

Fig. 12. CPT data of liquifiable soil.

3.5 Tracks on varved soils

There is one type of vulnerable soil, which is difficult to identify with soil unit characteristics, because it is the interaction between different units that causes failure rather than the soil unit itself. That is varved soils, an interbedded glacio-lacustrine soil made of thin beds of clay and silt. Upon loading, the clay is compressed, and water migrates into the silt beds. These then can locally liquefy. Varved soils are part of class F in the NEHRP classification [6], but there have been few problems with these soils in the railway network. These soils tend to be heavily overconsolidated and exhibit reasonably good mechanical characteristics. It is believed that good track drainage conditions provide a dissipation path and limit the risk of failure. Nevertheless, these soils need to be treated with care. However, varved soils are difficult to observe in CPTs because the readings are influenced by the surrounding soil up to a depth of approx. 30cm, whilst a single varve can only be several mm thick. Robertson [8] showed that varved soils have a specific pore pressure signature, as shown in Fig. 13.

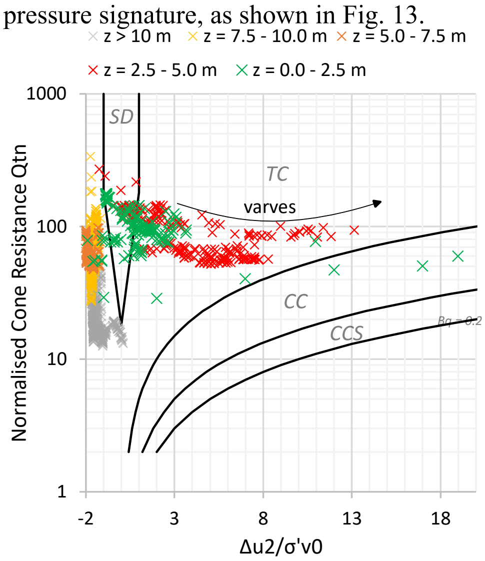

Fig. 13. CPT data of varved soils.

4 Conclusions

The Swiss railway network was mostly built in the 19th century along valley floors where the terrain is flat but prone to soft soil. Whilst this was satisfactory at the time, it is a challenge for modern railway traffic. The Swiss Federal Railways (SBB) have established an assessment process and verified many parts of the network. It was found that the seismic cone penetration test (sCPT) was the most efficient way to explore the track subsoil, albeit in conjunction with other methods. The shear wave velocity is a direct physical measurand of the small-strain behaviour, which is relevant for cyclic and dynamic problems. The CPT permits assessing the large-strain behaviour and, hence, allows the identification of soils which could undergo stiffness and strength losses.

Several examples of soils vulnerable to railway traffic are presented in the paper, highlighting the importance of these soils in areas with glacial geology.

Primary compression is often a problem for civil structures, but it is cyclic and dynamic behaviours which are more relevant for ageing railway infrastructure. While the primary consolidation has already taken place and the mechanical parameters of the soft soils are satisfactory, e.g., peat, the varying hydrogeological conditions due to climate change, internal erosion or the presence of additional supposedly counteractive measures can facilitate failure mechanisms during cyclic and dynamic loading. Some soils, such as extra-sensitive soils, underwent little to no primary consolidation and exhibit rapid failure mechanisms, which, although seldom, can be devastating.

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