

Geotechnical site assessment for ageing railway networks

Elliot James Fern

Swiss Federal Railways (SBB), Infrastructure, Network Installations & Technology, Track Bed, james.fern@sbb.ch

ABSTRACT: Railway traffic has and will increase substantially in Switzerland. Whilst much of the infrastructure was built in the late 19th century, it has been renewed several times, but the subsoil remained in place. Some soils consolidate with the traffic load and exhibit enhanced mechanical characteristics, but others can undergo strength and stiffness loss, which decreases the track capacity. Some soils can perform satisfactorily for small traffic loads but become critical when the traffic and speed increase. Ageing railway networks need regular assessment to meet modern traffic demands, and assessment methods are required. This paper presents a first-order assessment method and a site classification system that allows the asset manager to dedicate the technical and financial resources to where most needed. Railway networks tend to be large and screening techniques and low-cost investigation methods are required. The different railway-induced failure modes are reviewed, vulnerable soils identified, and critical sites defined. The technical verification of critical sites falls out of the scope of this paper.

KEYWORDS: Railway, soft soil, shear wave velocity, site characterisation.

1 INTRODUCTION

The Swiss railway network was built in the late 19th century and has been in use since then. Unlike other transportation infrastructure, the railway network was never designed for today's extensive traffic, high axle loads, high speeds and limited maintenance. Whilst the network has been extended and tracks have been renewed several times, the subsoil has remained in place and been subjected to two centuries of railway traffic. Predictions suggest that this traffic shall double in some areas of the network within the next 20 to 40 years. New failure modes arise from the changing traffic, such as fatigue-like failures. For instance, excess pore water pressure can accumulate in old embankments due to insufficient dissipation time between two train passages, something which is not considered when defining the traffic capacity of a given track. To guarantee the safety of the track bed, control maintenance costs, and ensure the overall quality of the network, critical sites must be identified for which a simple assessment method is required using measurable large-scale physical quantities and limited costs to assess the network.

There are different ways in which soil failures result in ground deformations, changing the track capacity and affecting maintenance costs and track safety. The different railway-related failure modes are reviewed in this paper, and vulnerable subsoils are defined. A site classification system is then proposed. It facilitates communication with asset managers and defines the extent of ground investigations and design work required in accordance with the Eurocodes (prEN 1997 2023).

Figure 1 illustrates the most common deformation patterns with ground densification, bearing capacity loss and embankment slumping being the most common. However, other mechanisms, such as boil ejecta, have been observed in recent years in the Swiss railway network. There is a long-lasting culture to assess track safety with visual inspections and deformation patterns, but different failure mechanisms can cause similar deformation patterns, making the identification of the most prevailing failure mechanism difficult. Moreover, this approach does not permit foreseeing high-risk, fast-developing and catastrophic failures of the subsoil, nor can it anticipate degrading situations due to traffic increase.

2 ASSESSMENT

An assessment process was developed to assess old railway networks and appreciate the geotechnical risks (Figure 2). Old railway networks differ from new ones by the limited available geotechnical information, the progressive increase in ground loading and a history of events and maintenance.

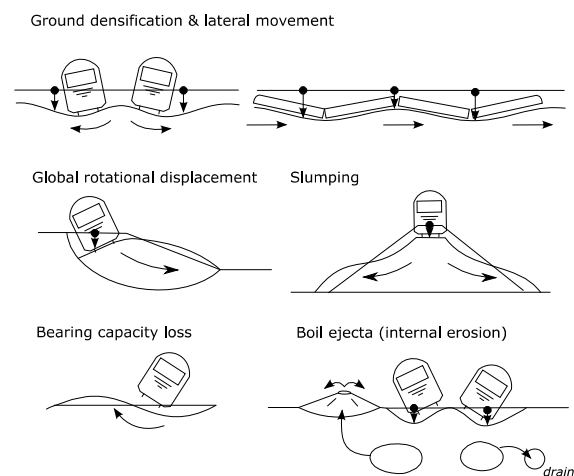


Figure 1. Subsoil failure modes of track beds.

The first step is the preliminary screening, which determines the likelihood of having vulnerable soils, which are defined later in this paper. If the likelihood is low with little changes in expected traffic and low maintenance, the geotechnical risk is considered low and acceptable. However, if the likelihood is high and insufficient data is available, field investigations are necessary. This follows the principles of the *geotechnical complexity class* and *geotechnical class* of the new Eurocode (prEN 1997 2023). Railway tracks are low-cost constructions per unit length but cover large areas and, thus, geotechnical investigations must also be low-cost, approx. USD 20 to 40 per metre length in Switzerland. Hence, preliminary screening of sites is necessary to control investigation costs. This is done by using geological and geotechnical maps. Track bed performance and maintenance analyses can sometimes identify already-failed grounds, but the screening must not be limited to the history of events and must consider future traffic. The shear wave velocity of the ground v_s appears to be a good measurand to assess the geotechnical risk as it can be obtained with conventional techniques (e.g., seismic piezocones, geophysics) or new technology such as distributed acoustic sensing using existing dark fibres along the track bed (Ajo-Franklin et al. 2019; Obando Hernandez et al. 2023).

If vulnerable soils are identified, the ground mobilisation must be verified. If these soils have sufficient strength and stiffness, then the geotechnical risk can be considered low and acceptable. However, if plastic deformation is expected then the post-failure behaviour must be analysed. These tasks fall outside the scope of this paper.

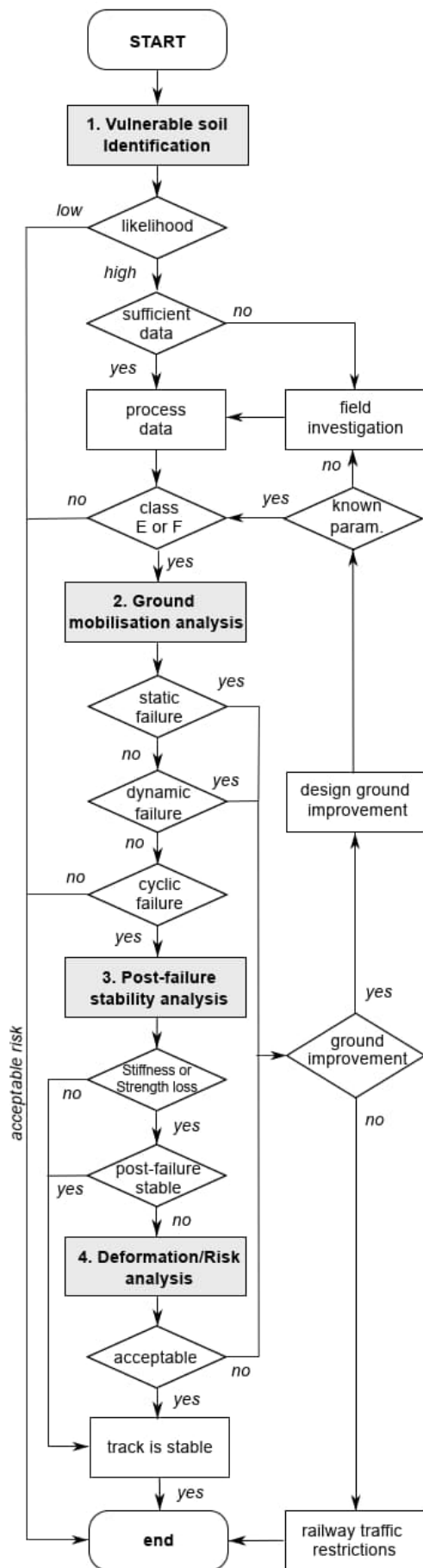


Figure 2. Assessment flow chart.

Failed soil, even liquefied, still has a strength and stiffness and, in some cases, this can be sufficient to guarantee safety despite inducing higher maintenance. A risk is considered acceptable if the identification of the deformation and its remediation through maintenance work can be done faster than the failure mechanism. In some rare cases, traffic restrictions can be put in place to decrease the dynamic load on the subsoil and stabilise the situation. The asset owner is then free to carry out the remediation work to increase the capacity of the track. Much of the assessment requires identifying and understanding how soil fails under traffic loads.

3 VULNERABLE SOILS

Vulnerable soils are soils that can undergo excessive, difficult-to-predict or uncontrollable deformations for a given railway traffic. This includes soils that can undergo significant strength or stiffness loss. A given subsoil can be satisfactory for a certain railway traffic, but become vulnerable for higher train speeds, axle loads, train lengths, or train passages. The train length increases the duration of a given cyclic load and causes a greater build-up of excess pore pressure. The number of trains influences the time between two train passages and, hence, the available time for excess pore pressure dissipation.

Table 1 lists the different failure modes alongside post-failure behaviours, identification criteria and associated risk. The shear wave velocity v_s appears to be a good measurand for preliminary investigations, as it can be measured in the field and relates directly to the small-strain shear modulus G_0 and soil density ρ as shown in Eq. (1).

$$G_0 = \rho v_s^2 \quad (1)$$

The following soils are considered vulnerable soils for the medium-high speed ($v_{\text{train}} < 240$ km/h) railway networks:

- *Weak soils* have little shear strength. These tend to be normally or lightly overconsolidated soils and fail in undrained conditions; the undrained shear strength c_u is smaller than the drained shear strength with post-failure strength/stiffness losses. The short-term nil-volume conditions imply no track deformation. Weak soils tend to be loose and of high plasticity, albeit not exclusively. ISO 14688-2 (2017) defines weak soils as $c_u < 40$ kPa and very weak as $c_u < 20$ kPa, though the wording changes between languages. These thresholds are sometimes set to 50 and 25 kPa, respectively (ASTM D653 2022). Very weak soils are vulnerable to railway traffic. L'Heureux and Long (2017) reviewed the relationship between the shear wave velocity and the undrained strength (Eq. (2)) and suggest $v_s < 120$ m/s as an identification threshold.

$$v_s = 13.32 c_u^{0.72} \quad (2)$$

- *Sensitive soils* have a significantly lower residual shear strength than peak strength. They can undergo flow liquefaction, which is uncontrollable. ISO 14688-2 (2017) defines medium-high sensitive soils as $8 < S_t < 30$ and highly sensitive as $S_t > 30$; Skempton (1954) refers to these as extra-sensitive soils and quick clays. Quick-clays are not present in the Alps, but extra-sensitive lacustrine soils are (Huder 1963) and have caused accidents in the past. Their strong microstructure infers higher shear wave velocities (e.g., Lontzetidis et al. 2022) and mislead preliminary investigations. However, the sensitivity easily identifiable with seismic piezocones (sCPTu) because differences emerge between the estimated and measured values ($v_s^{\text{est}} \ll v_s^{\text{meas}}$); CPT correlations of shear wave velocities are for normally structured soils.

Table 1. Failure modes of track bed subsoil for medium-high speed railways.

Failure mode	Soil type	Post-failure behaviour	Identification	Danger
<u>Monotonic/static:</u>				
Drained shear	Dilative soils	Brittle with softening	$v_s > 120$ m/s	Low
	Special	Brittle for metastable soils	$v_s^{est} \neq v_s^{meas}$	High
Undrained shear	Saturated contractive,	Mostly progressive	$v_s < 120$ m/s	Med-high
	Sensitive/special soils	Can evolve into flow liquefaction	(s)CPTu	High
Primary compression	Mostly soft org. soils & some clays	Progressive	$v_s < 145$ m/s	Med.-high to extreme
Secondary compression	Mostly org. soils & some clays	Progressive & continuous	(s)CPTu	Low to med.-high
<u>Monotonic/static or dynamic/cyclic:</u>				
Collapse	Any metastable structure	Brittle. Can evolve into flow liquefaction when saturated.	$v_s^{est} \ll v_s^{meas}$	Med.-high to high
Complex	Interbedded soils or with strong microstructure	Variable	(s)CPTu	Low to extreme
Flow liquefaction	Any metastable saturated soil, contractive silts & sands, extra-sensitive clays	Brittle & fast. large displacements depending on kinematic conditions. Unstable post-event. Significant softening for contractive soils	$v_s < 150$ m/s Liquefied: $v_s \rightarrow 0$	High to extreme
<u>Dynamic/cyclic:</u>				
Cyclic liquefaction	Almost all saturated sands with limited deformation in clays. Occurs faster in contractive soils	Progressive to brittle. Significant deformation during loading cycle but stable at post-failure	sCPTu	Med.-high
Cyclic mobility	Mostly clayey soils with limited deformations. Contractive & dilative soils	Progressive. Limited deformation but results in high maintenance.	sCPTu	Low
Dynamic	Mostly soft soils	Brittle & fast, depends on damping capacity of track bed	$v_{train} < 0.62 v_R$ with $v_R \approx 0.9 v_s$	Extreme

- *Collapsible soils* have metastable microstructures that can undergo a sudden and abrupt volume reduction in drained conditions. They are characterised by a high void ratio, an inherent low intergranular bond strength and tend to be extra-sensitive (Jefferson and Rogers 2012). The identification of collapsible soil is possible with sCPTu, as shown by Robertson (2016). They have unusually high small-strain stiffness with the empirical stiffness parameter $K_G \gg 100$ whilst exhibiting contractive-like behaviours ($CD < 70$).
- *Soft soils* are soils which can deform significantly under conventional loads. *Compressible* soils are more specifically those with a strong volume reduction. Unlike collapsible soils, soft soils tend to have a stable soil structure, and the deformations tend to be progressive. This changes the post-failure behaviour and the associated geotechnical risk. Soft soils tend to be young soils (Holocene epoch) and are found mostly in Alpine valley floors and are an important part of glacial geology. There is no universal criterion to define soft soils, as it depends on the maximum acceptable deformation. Li et al. (2016) define soft track bed subsoils with a resilient stiffness of $E'_u < 28$ MPa, which relates the Swiss federal regulations for new railways with a minimum constrained modulus of $M > 14$ MPa. According to L'Heureux and Long (2017), this relates to $v_s \approx 145$ m/s as given in Eq. (3).

$$M = 0.0001 v_s^{2.212} \quad (3)$$

Soft soils tend to be contractive, but ISO 14688-2 (2017) defines soft soils with the consistency index ($I_c < 0.5$) This index refers to the states rather than its ability to contract (Schofield 1980). The state parameter is an equivalent with $\psi < 0.1$ as a conservative identification criterion (Jefferies and Been 2016). The contractive-dilatative index (Robertson 2016) can also be used with

$CD < 70$, and shown in the SBTn chart (Figure 3). The shear wave velocity must be normalised (Kayen et al. 2013) to be plotted in the SBTn chart (Robertson and Cabal 2022) (Figure 3). $CD = 70$ line occurring around $v_{s1} = 175$ m/s and relates to $v_s = 150$ m/s at 2-3m depth, a critical depth for the track bed.

- *Liquefiable soil* can fail due to an increase in pore water pressure and, thus, a decrease in mean effective stress. It can result in strength/stiffness loss, allowing the soil to behave like a fluid, but it differs in the way energy is dissipated; granular soils dissipate energy through intergranular friction, but fluids through viscosity. Different types of liquefaction exist. *Flow liquefaction* is characterised by an unstable post-failure configuration, allowing the soil to behave as a fluid once the load is removed.

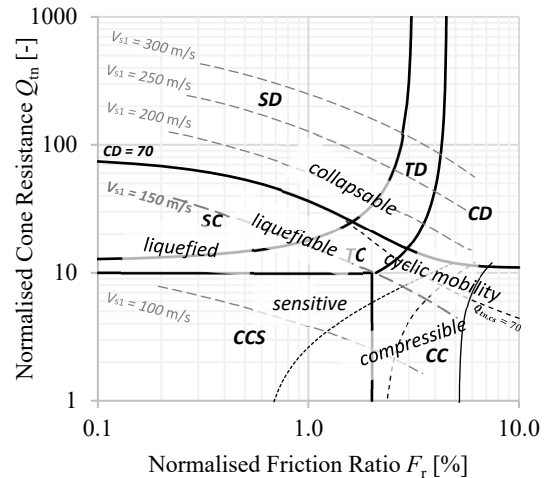


Figure 3. Normalised soil behaviour trend (SBTn) chart and associated failure mechanisms.

It happens mostly in contractive soils for which the reduction in pore space associated with the stress-dilatancy response is greater than the corresponding work hardening of the skeleton to support the increased stress. The soil is then *liquefied* with a near-to-nil stiffness and thus a very small shear wave velocity ($v_s \rightarrow 0$). *Cyclic liquefaction* is triggered by cyclic loading and is characterised by a stable post-failure configuration, in which deformation ceases upon load removal. The volumetric strain is caused by the compression brought by the load. All soils can be subject to cyclic liquefaction, but low-plasticity soils tend to be more sensitive as the limiting strain threshold γ_{th} is lower (Vucetic 1994). Several cases have been observed in the railway network and are identifiable by the presence of boil ejecta, referred to as mud pumping in the railway community. *Cyclic mobility* occurs when the excess pore pressure is generated at the location of higher stress and migrates. It can cause strength and stiffness loss elsewhere. It occurs more often in higher-plasticity soils. This is well known in railway engineering and results in ballast pockets with water ponding.

The cyclic resistance ratio (*CRR*) can be estimated with sCPTu (Schneider et al. 2008; Schneider and Moss 2011). It is, however, known that loose soils at low confining pressures are the most likely to liquefy, and these tend to have $v_s < 150$ to 200 m/s (Andrus and Stokoe 2000). Both cyclic liquefaction and cyclic mobility are fatigue-like failures, which have been observed throughout the network. The number of cases is expected to increase due to the ageing network and a substantial increase in train traffic.

- *Dynamic failures* result from the accumulation of energy in the ground. It can lead to uncontrolled and fast degradation of the subsoil, albeit less catastrophic for soils than built structures (Kramer 1996). These failures occur when the train speed coincides with the critical speed (Norén-Cosgriff et al. 2018). This relates to the Rayleigh wave velocity for single-strata subsoil (Madshus and Kaynia 2000). Yang et al. (2009) showed that the dynamic effects become noticeable as of 10% of the Rayleigh wave velocity v_R and significant as of 50%. Duley (2018) reviewed several cases shown in Figure 4 and the data can be modelled with Eq. (4).

$$\frac{\Delta s_{dyn}}{\Delta s_{stat}} = 1 + A \exp\left(B \frac{v_{train}}{v_R}\right) \quad (4)$$

with Δs_{dyn} and Δs_{stat} the dynamic and static rail deflection, $A = 0.005$ and $B = 6.7$ two model parameters. Eq. (4) masks the fact that the static rail deflection can alone be unacceptable for compressible soils (Powrie 2024) and that the transition from static to dynamic regimes is brittle for soft soils (Figure 5). Conay et al. (2023) suggest setting a deflection ratio threshold at $v_{train}/v_R = 0.625$ defining the minimum required ground velocity. Note that this approach neglects any site reflection effects.

- *Special soils* refer to soil units composed of different types of soil and/or with distinct bedding or microstructure for which complex and combined failure mechanisms take place. Varved soils are complex interbedded soils of glacial origin with a strong interaction between each layer of silt and clay. There is no unique criterion to identify such soils.
- *Expansive soils, acid soils and soluble grounds* are not covered in this paper as well as shakedown and ratcheting because of the smaller induced deformation.

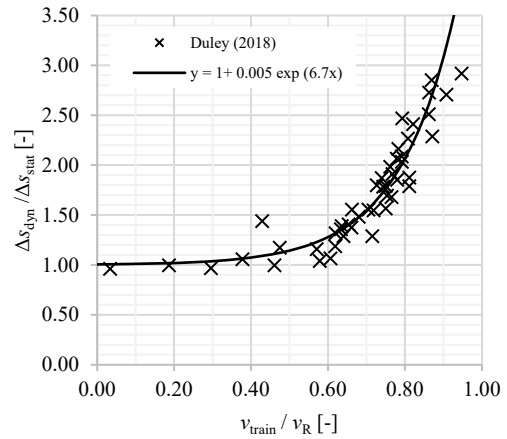


Figure 4. Effect of train speed on track displacements.

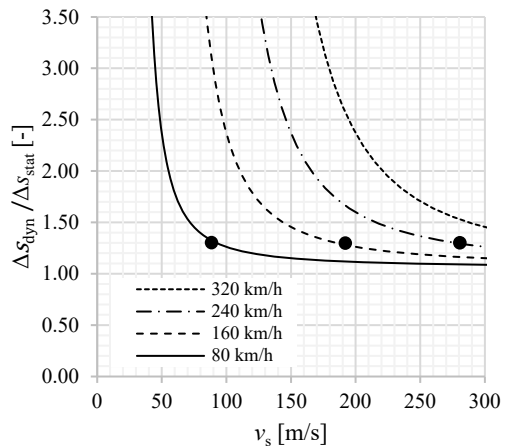


Figure 5. Critical shear wave velocity with respect to train speed.

3.1 Organic soils

Most organic soils are soft, compressible and subject to secondary consolidation, but not all vulnerable soils are organic. There is no universal definition for organic soils and the rules of division are diffuse. ISO 14688-2 (2017) defines organic soils as $2\% < OC < 20\%$, with *OC* the organic content. Peat, dy and gyttja are not explicitly defined in this standard. Peat and dy differ from one another by their organic compounds related to the decaying mechanism and this affects their mechanical characteristics. Dy is often mistaken for peat because they look alike and can be identified by CPTs as they have a friction ratio $F_R > 4\%$; other CPT trends and correlations permit distinguishing types of organic soils but shall not be discussed in this paper. Gytja results from the decay of remains in oligotrophic environments and has $OC < 14\%$ (Larsson 1990). Gytja is difficult to identify as it maps in the SBTn as soft silt/clay-like soils. CPT correlations do not always hold true for these organic soils. However, all have very low shear wave velocities (typically $v_s \ll 100$ m/s).

Peat is characterised by a high porosity making it very compressible. However, fibrous peat exhibits a surprisingly good behaviour when subjected to cyclic loading because the fibres provide additional resistance (Zwanenburg et al. 2020). Peat is not necessarily problematic for existing railways, which have already undergone primary consolidation. However, other organic soils, especially organic silts, appear to be more problematic. Peat, Gytja and dy have been found in the Swiss railway network. More importantly, the construction of several embankments in the 1850s were carried out with organic soils and have been found, even peat. Peat has also been used in the past as frost protection in other countries.

4 SITE CLASSIFICATION & ASSET MANAGEMENT

Understanding and identifying the prevailing failure mechanism of a given soil layer is of importance, but it is the depth and interactions with other soil layers and the railway infrastructure which define whether a given vulnerable soil is critical or not.

Three stress regions can be defined when studying the stress diffusion of railway traffic in the ground and considering a track bed pressure of 40 kPa. The first is the cyclic stress reversal region, which goes down to a depth of approx. 3m. Vulnerable soils at these depths are mostly critical. The second region is still significantly affected by the cyclic stress, but without stress reversal and goes down to 6m. The third region is dominated by the static loads with a small cyclic stress and goes down to approximately 10m. This depth corresponds to the ideal field investigation depth and relates to the depth suggested by Costa et al. (2020). However, the critical depth can vary from case to case and should ideally go down to the stiffer layers. The track stiffness is often used for railway design (e.g., Selig and Waters 1994) and represents the different infrastructure and subsoil stiffnesses as a single equivalent spring. Because the shear wave velocity relates directly to the small-strain stiffness, an equivalent shear wave velocity \bar{v}_s can be defined (Eq. (5)).

$$\bar{v}_s = \sum_{i=0}^{j|z=z_{crit}} \frac{v_{si}d_i}{d_i} \quad (5)$$

where v_{si} is the shear wave velocity of a given soil layer, d_i its thickness and z_{crit} the critical depth.

The determination of the critical depth to be considered in the assessment is difficult. It is typically 10m for a homogeneous, isotropic and infinitely deep soil stratum and is denoted v_{s10} by analogy to NEHRP v_{s30} . However, it can also be significantly shallower when a thin and soft layer rests on a stiff ground because the stiffer layer will significantly increase the equivalent shear wave velocity and mask the presence of the critical soft layer.

Table 2 gives the site classification. It is based on a default depth of 10m. v_{s10} , which can be converted to v_{s30} with the work of Boore (2004). Classes E and F are for critical sites with vulnerable soils. The thresholds were defined from the different failure mechanisms, and these relate well to those of the NEHRP system. Network Rail (2020) and the Eurocode (EN 1998 2004) qualify these classes as critical, and tracks require specific design. Class A to D sites only require additional verifications if ground-related damage is observed. The new Eurocode (prEN 1997 2023) provides more details on the design requirements for critical sites, and class E & F sites correspond to geotechnical complexity class GCC3.

Table 2. Site classification for medium-high speed railway tracks.

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
	115 – 140	145 – 180	20 - 40
E	or high-plasticity ($I_p > 20\%$), loose ($I_c < 0.5$, $I_D < 35\%$), weak ($c_u < 40$ kPa) or organic ($2\% < OC < 20\%$) soils with thickness $d_i > 0.5$ m within 10 m depth.		
	< 115	< 145	< 20
F	or liquefied/liquefiable, with a strong microstructure, very sensitive ($S_t > 8$), very organic ($OC > 20\%$) or very weak ($c_u < 20$ kPa) soils with thickness $d_i > 0.5$ m within 10 m depth, or Class E with thickness $d_i > 8$ m, or with $v_{train} > 0.62 v_R$ over $d_i > 0.5$ m.		

The compatibility with the NEHRP system permits using existing earthquake maps to identify potentially critical tracks in the absence of any field measurements. Although of insufficient quality for design, this information is paramount when screening the railway network to identify potentially critical sites and justifying expenditure for site exploration as well as allocating realistic budgets for the projects. Experience shows that tracks on soft soils are significantly more expensive than on good ground. This includes costs for initial construction, maintenance costs (e.g. tamping), component replacement, and eventual reconstruction. It is even more expensive if ground treatment is required.

The Eurocode (EN 1998 2004) sets specific requirements for class F sites, and this can be used for railways engineering because trains can be considered as a moving cyclic and dynamic load of low magnitude but many cycles. The next generation of Eurocodes (prEN 1997 2023) gives an even better framework for such cases.

The identification of soft soil at a site is required early on in construction projects (Figure 2) and is important for asset managers. The first-order estimation of the critical train speed and the risk of soil fatigue-like behaviours is on the other hand crucial for the long-term management of infrastructure as it permits planning long-term investment schemes as well as defining threshold criteria until when the infrastructure should be used before undergoing significant damage, which results in significantly higher remediation costs. It can result in traffic reduction measures such as decreasing the maximum trains speed or the number of train passages, and this has a direct impact on the traffic capacity of track and, thus, the financial performance of the company. Critical sites are now integrated into the life-cycle cost and investment strategy of the Swiss Federal Railways.

5 CONCLUSION

The Swiss railway network was built in the late 19th Century and has been in use ever since. However, the railway traffic has substantially increased in terms of train speed, train length, axle load and train passages. Many parts of the infrastructure have been renewed and upgraded, but the subsoil has remained in place, and new ground failures have been observed (Figure 1). An assessment process (Figure 2) was developed for track renewals and the site classification (Table 2) defines whether a site is critical, if it requires additional site exploration, and if advanced verifications are needed. The assessment is based on the different failure mechanisms presented in Table 1 and permits appreciate the rate at which failure-induced deformations take place and the related dangers. The site classification is compatible with other systems, which are often public information and can be used when site data is not available. The review of the different failure mechanisms showed that only class E and F sites are critical for the track bed, and these sites often require significant investment and monitoring.

The shear wave velocity is found to be a good first-order proxy for vulnerable soils. However, this measurand can be misleading when used alone and dealing with natural soils with strong or unusual soil structures; the seismic waves travel mostly through the solid matter and governed by the intergranular contacts. Cemented soils tend to have higher shear wave velocity, whereas liquified soils a lower one. The seismic piezocone (sCPTu) is currently the most effective and complete method to assess the track bed subsoil but distributed acoustic sensing (DAS) using existing telecommunication fibre optic cables now permits large-scale assessments of networks at very low cost and can monitor the evolution of the ground. However,

some technological developments are still required for it to better capture the first 2m of soil and automatically process the large amount of data.

6 ACKNOWLEDGEMENTS

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