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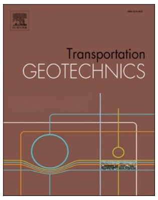

Water content variation of railway track sub-ballast layer in seasonal frost area: A case study from Finland

Juha Latvala [*,1], Pauli Kolisoja [1], Heikki Luomala [1]

Research Centre Terra, Tampere University, Finland

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ABSTRACT

Many previous international studies have found a clear relationship between railway track water content and track geometry problems. The proper drainage of substructures is important in ensuring the safe and efficient operation of tracks. This importance will be emphasized in the future with the increasing frequency of extreme weather phenomena and the raising axle weights of train traffic. In many studies, excessive water content has been found to cause excessive geometry deterioration and mud pumping. These problems are usually related to thin substructure layers. However, in this case study, Finland, track substructures are thick due to frost protection requirements and behave differently to thin substructures. In this study, the long-term water content of three instrumented test sites was monitored to study the seasonal and freeze–thaw effects, as well as the effects of drainage improvement made at one site. In a previously reported part of the same research project, the measured water contents were used in an extensive cyclic loading triaxial test series evaluating the loading resistance of substructure materials taken from the same sites. The drainage improvement resulted in a marked decrease in the average water content at the drainage improvement test site. Simultaneously, high momentary water content values also disappeared. The role of capillary water was observed to be less than expected on Finnish railways.

Introduction

In the future, many countries intend to increase the axle weights and speeds of trains. Simultaneously, climate change is predicted to further change the global climate with extreme phenomena. Consequently, floods, heavy rains, and extreme drought will become common in some places. [12,30]. In Finland, annual rainfall has already increased and this has been predicted to continue into the coming decades [25,24]. The intensity of individual rains has also been predicted to increase [18]. The effects of a changing climate on infrastructure are causing international concern [22]. For example, a study conducted in Sweden [20] stated that the changing climate would probably increase the unfavorable conditions on Sweden's rail network, and the effects of the changing conditions should be considered as early as possible. The sustainability of infrastructures is an important target, and long-lasting climate-resilient structures save natural resources.

Excessive water weakens different kinds of earth structures. Thus, investigating the effects of track water content on loading resistance to identify the potential benefits of improved drainage is important. To evaluate the loading resistance of track substructure materials, the long-term seasonal water content including also the freeze–thaw effects of substructure materials are needed. There is an obvious lack of that information in Nordic climatic countries like Finland. Thus, three measuring stations were built at different sites in Finland where the drainage was inoperative to determine the water content of the substructure layers. Material samples were also collected from the sub-ballast layer of these sites. These materials have been tested in the laboratory with cyclic loading triaxial tests at different water contents, and Latvala et al. [17] have reported the results.

In this paper, the measurement results of the water contents at the three monitoring stations are presented. When analyzing the results, the most important research questions are as follows:

(1) What magnitudes of seasonal water content appear in the sub-ballast layer of an existing track in different locations?
(2) What is the effect of rain on the water content of track sub-ballast materials?
(3) How high values of water content capillary rise causes above the groundwater level?

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* Corresponding author.
E-mail addresses: juha.latvala@tuni.fi (J. Latvala), pauli.kolisoja@tuni.fi (P. Kolisoja), heikki.luomala@tuni.fi (H. Luomala).
[1] Postal address: P.O. Box 600, FI-33014 Tampere University, Finland.

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(4) To what extent does drainage improvement influence the water content of the sub-ballast layer?

Literature review

The effects of the water content in the track substructure.

Cyclic loading and fine-grained materials with excessive water content are bad combination with regard to track geometry stability [19]. The effects of excessive water content appear either as an increased need for maintenance or, in flooding situations, even as derailments or significant damages [10]. Even a small increase in water content can cause a significant decrease in loading resistance [5], and severe drainage issues can lead to landslides [32]. Problems most likely occur in old sections of the track that do not meet the current requirements and design criteria [20]. However, water-related issues can also appear on high-speed tracks in cold areas [5,33]. Determining the properties of ballast, sub-ballast layers, and subsoil to distinguish the reasons for weak track geometry stability is usually necessary [1].

The relationship between track geometry problems and the water content of track substructure layers is complex. Many studies and laboratory tests have shown that a track is usually vulnerable to geometry deterioration even long after flooding [9]. According to Ghataora and Rushton [8], it can take over four days for water to dry from a single-track section but up to 10 days from a double-track section drained at one side. Wang et al. [31] observed in their ground penetrating radar (GPR) studies that high water content has been detected more in transitional structures than in line sections. This usually causes problems because the dynamic forces are increased in transition zones [27]. Consequently, Wang et al. [31] proposed that the drainages in transition structures should be more effective than in line sections. High water content can also reduce the resonance frequency of the ground and cause vibration issues when train speeds increase [14].

Development of permanent deformations are sometimes tried to be explained by the change in resilient modulus. However, in the study of Latvala et al. [17], the resilient moduli values for Finnish track sub-ballast materials could not forecast the development of permanent deformations in a long-lasting cyclic loading test series. The positive effect of sand blanketing and the intermediate layer below the ballast layer on geometry stability has been recognized Duong et al. [3] and Hasnayn et al. [11]. This layer can prevent typical problems, such as erosion and mud pumping. If the sub-ballast layer is made of coarser materials, it is more resistant to cyclic loading, even in high saturation degrees [28]. Notably, the fines content of substructural layers seems to play a dual role. Duong et al. [4] observed that with reduced water content, the increased fines content reduced permanent deformation. When saturated, the strength of the material with more fines was weakened significantly, and deformation accelerated. This observation is critical because too-high fines contents are often seen in old substructure layer materials. In Finland, due to frost protection, the. total height of non-frost susceptible materials (K) needs to be at least 2,0 m without artificial frost insulation layers, which is exceptionally large than in comparison to many other countries. In Finland, the thickness of the ballast layer is usually 550 mm and the sand blanketing below ballast is 300 mm (Fig. 1). The thickness of the sub-ballast layer varies depending on geographical location to fulfill the frost protection requirements. Even though older track sections are usually not fulfilling these requirement, there is no subsoil-related mud pumping problems in Finland.

the measurement techniques of the water content in track substructures

Knowing the actual water content in track substructures is critical in evaluating water content effects. The water content in earth structures can be measured using several techniques. The most traditional method is taking material samples [23]. However, this disturbs the substructure and is labor-intensive [15]. The development of technology has enabled the use of new, nondestructive methods, such as GPR [29], in substructure evaluation with faster implementation. These nondestructive methods have the advantage of gathering more measurement data. Between these methods lies the time domain reflectometer (TDR) method, where a sensor is lowered into a plastic pipe installed in the structure. This method was tested by Ižvolt et al. [13] when performing calibrations for coarse-grained materials, and good accuracy was achieved.

The GPR effectively produces longitudinal data on layer structures and the water content of track substructures. However, subsequent application requires complex signal processing [21]. To reliably determine actual water content, GPR results should be calibrated using samples and test pits [31]. If the lower part of the ballast layer is contaminated with fine particles, the GPR does not penetrate this layer adequately [1]. Another method that has aroused interest is electrical resistivity tomography (ERT), which is based on changes in the earth's resistance due to the influence of water content. Chambers et al. [2] examined the water content of an old railway embankment using ERT. The results were promising and interesting, but the method was complex to implement. In the depth and lateral directions of the embankment, there was a clear variation in the water content, but the embankment was heterogeneous in terms of materials. They presented that in determining water content, petrophysical equations between the water content, the resistance, and the temperature measurement of the embankment were required since resistivity changes with temperature. In Finland and other northern countries, the water content in road substructures has been measured using Percostations, which measure dielectricity, electrical conductivity, and temperatures at different road structure depths [16].

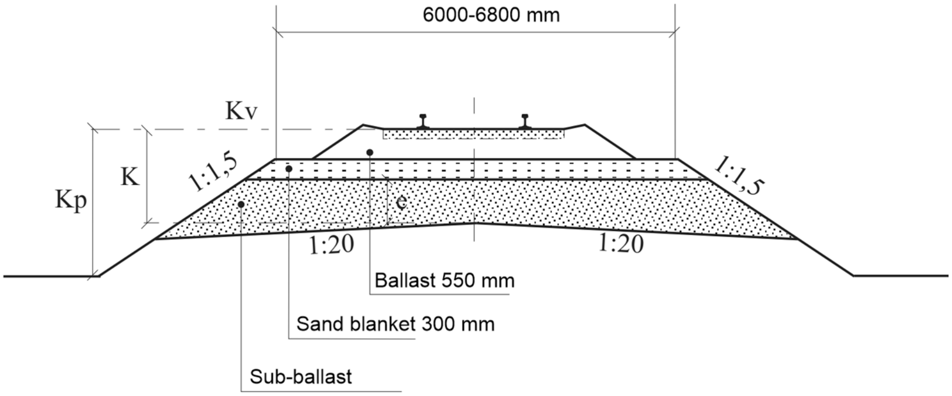

Fig. 1. The cross-section of a typical single line Finnish track [7].

Materials and methods

Description of measurement sites

Water content measuring stations were installed at three sites on the Rantarata track line, which runs along the southern coast of Finland, in various cross-sections where the drainage was assumed to be faulty. Repeated track geometry deterioration problems have occurred at all three sites or in their vicinities. The subsoil conditions in Rantarata are known to change quickly from bedrock cuts to soft clay layers over 10 m thick. The original idea was to improve the drainage of all three sites and determine the effects of drainage improvement. However, within this monitoring period, only the drainage at kilometer (Km) 44 was improved.

Km 44

The monitoring site at Km 44 is located in a flat area where the track is about the height of a ballast layer higher than the surrounding terrain. This is shown in an overview of the area before and after drainage improvement, taken on July 04, 2017, and January 29, 2020 (Fig. 2). The subsoil under the track is clay with a thickness of about 16–18 m. During sensor installation, the ballast layer thickness was found to be much thicker than normal 0,55 m and the ballast particles were found up to the depth of 1 m mixed with sub-ballast material. The track has presumably sunk into the clay layer over time due to consolidation settlement. The prevailing drainage condition of the site was challenging, as the site is located on a flat area, and the surrounding terrain partly slopes in the direction of the track. There was a short ditch on one side of the track near the measuring point, and on the other side, a small ditch at the edge of the field, which was already quite far away. The water level in the ditches was high during all inspection visits, indicating that the water was not getting out of the track area. At the turn of 2019 until 2020, drainage improvement was conducted at the site by installing a drain on the side of the measuring station to the depth of −1,85 m. After that, the area was shaped, and the ditches were deepened. Simultaneously, the water drainage path outside the track area was also improved.

Km 98

The track at Km 98 is located on an embankment in a field (Fig. 3). The site represents a typical Finnish track. The subsoil is mainly silty clay, but there are also layers of fine sand near the measurement station.

Fig. 2. The areal picture of Km 44 before and after the drainage improvement from opposite perspectives. The track is on flat terrain, and the drainage was not working properly. Photos taken on May 04, 2017, and January 29, 2020.

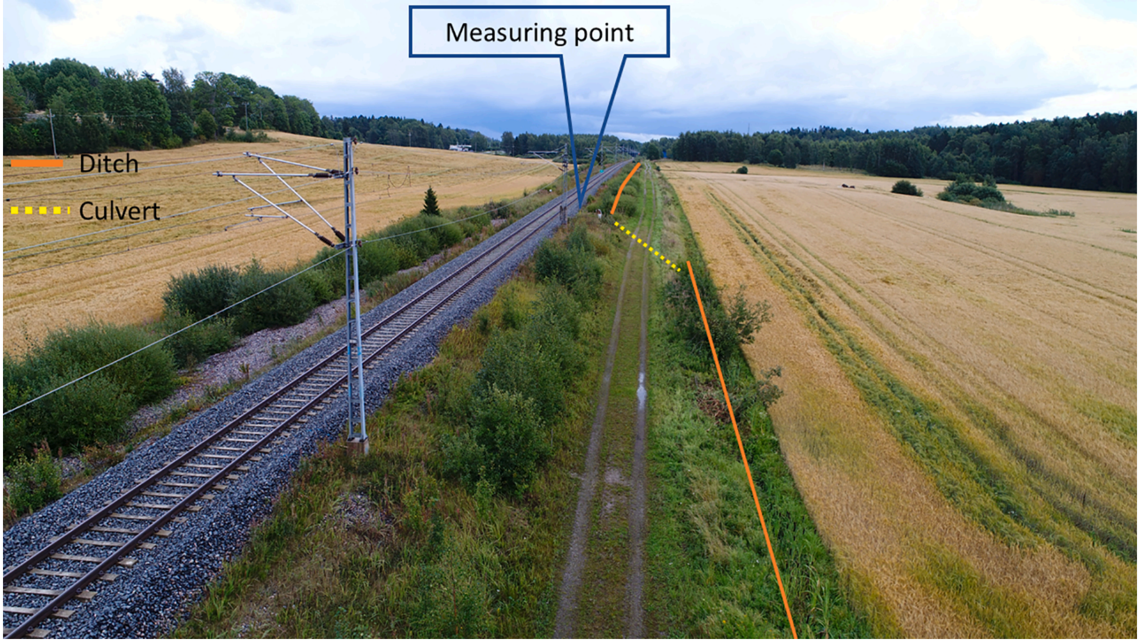

Fig. 3. The areal picture of Km 98 eastward. The track runs through a field on an embankment. The site is “average” and represents a typical Finnish track. Photo taken on August 22, 2017.

The thickness of the soft soil layer under the measuring station is 13.5–14.5 m. The drainage condition of the site can be considered typical. On the south side of the track (on the right in the picture), there is a ditch in reasonable condition, which, however, ends at the monitoring station. The water was supposed to flow from the culvert running under the service road, but the culvert was inspected to be in poor condition. On the north side of the track, there is no actual ditch between the field and the track. Improving the drainage at the site is easily possible by digging up the existing ditch, repairing the culvert, and making a proper ditch on the north side of the track.

Km 137

Km 137 is significantly different from the other two sites, as it is located next to a sand esker (Fig. 4). The surface of the ground is very dry. Sites like this are suspected to have some underground water flow due to the height differences and the esker. Consequently, the site was selected as one monitoring site. The thickness of the sand layer in the direction of the track varies. At the monitoring station, the sounding rods penetrated 3.9–4.0 m deep. After that, there was a hard bottom, probably a bedrock. Near the measuring station, 100–200 m away, there is a rock cut and a tunnel through the rock at the same distance on the other side. Therefore, the subsoil conditions vary rapidly at this site.

Fig. 4. The southwest areal picture of Km 137. The site is located near the sand esker that slopes in the direction of the track. Photo taken on May 04, 2017.

the measurement system

With the help of measurement stations, determining the effects of drainage arrangement changes and studying the seasonal effects is possible. The stations are equipped with sensors measuring the following quantities:

1) Displacement sensors measuring vertical displacements of the track
2) Sensors measuring the water content, temperature, and electrical conductivity of the sub-ballast layer. Temperature sensors are used to determine frost penetration depth.
3) Sensors measuring the suction pressure in the sub-ballast layer
4) Tensiometers at two different depths
5) Groundwater level pipes and sensors
6) Water level measurement in ditches
7) Rain gauges

Fig. 5 shows an example of the cross-section of the sensors installed at monitoring stations in the cross-section of the railway embankment. The water content measurement of the substructure was mainly based on TDR-type sensors (Decagon GS1/GS3) under the track shoulder. The suction pressure was also measured, but the system did not work as reliably as planned. The sampling rate of these sensors was 30 min so that the effects of individual rains could be detected from the data. For the water content sensors, the general coefficient provided by the manufacturer was used as the calibration coefficient. This general coefficient should be suitable for measuring all kinds of sand materials because the TDR frequency of sensor is high (70 MHz). Determining a more accurate calibration coefficient would have been challenging, as there was a noticeable vertical variation in the materials of the sub-ballast layer. Consequently, many sensors would have had to be calibrated separately. The volumetric water content was converted into saturation degrees using the measured maximum volumetric water content. The saturated state was observable in the lower sensors. For converting the upper sensors' reading to saturation degrees, the theoretical values calculated from laboratory tests were used with the help of the lower sensors' maximum water contents. Thus, the measurement resolution was assumed to be about 10 %, in terms of degree. In the cyclic loading triaxial tests, the biggest changes appeared above a 70 % saturation degree [17], and those moments could be observed from field measurement data.

Sub-ballast material properties of measurement sites

The material samples from the sub-ballast layers of the sites were collected during the installation of measurement stations. These samples have been examined in the laboratory. One additional good-quality reference material was also included in the laboratory tests, which fulfilled the Finnish Transport Infrastructure Agency (FTIA) requirements for the sub-ballast layer at the time of the study. Fig. 6 shows the grain size distribution curves of the materials, and Table 1 shows the typical geotechnical parameters. Only one of the samples, the one taken from Km 44, fulfilled the granularity requirements. All the samples taken from the field differed from the reference material, mainly on the finer end of the grading curve. The Km 137 material was mostly out of the FTIA grading limits due to its small average particle size, and as a uniformly-grained material, it was poorly compactable.

Laboratory capillarity measurements

The determinations of the capillary rise height were performed on the material samples from the field sites in the laboratory. The tests were related to a research project that investigated the effect of capillarity on the loading resistance of materials and the differences in methods used for determining the height of capillary rise [26]. Fig. 7 shows the most important results from the capillarity tests performed in the open capillary rise pipes. These tests have been performed by adapting the SFS-EN 1097–10 standard [6], but the samples have been disassembled in layers to determine the vertical water content profile. The saturation degree above the water level seems to decrease rapidly when the distance from the water level increases. At 20 cm from the water surface, the degree of saturation was around 50–70 %, and at 35 cm above the free water level, it was less than 50 % for all the examined materials. The material density greatly affects the maximum capillary rise, as indicated by the wetting of particle surfaces in the capillary test arrangement. For example, in the Km 44 material, the difference between the very dense (2.11 g/cm^3, Rc (Relative Compaction) 103 %) and loose (1.89 g/cm^3, Rc 93 %) states was about 35 cm. In these tests, the maximum height of capillary rise is also time-dependent, as the water continued to rise even after 50 days with sand materials. However, the rising rate slowed significantly but continued slowly. As aforementioned, the test sites' materials differed from the current FTIA guidelines and contained too many fine particles, so their capillary rise height can be considered too high for substructure materials.

Results of water content measurements

The measurement results are continuous data from July 2017 to the beginning of 2022. Shorter periods are also examined to study the effects of individual rains. The measured water content at the sites is illustrated with heatmap-type images, where the saturation ratio of the sub-ballast layer is shown using colors. The installation depth of the sensors varied

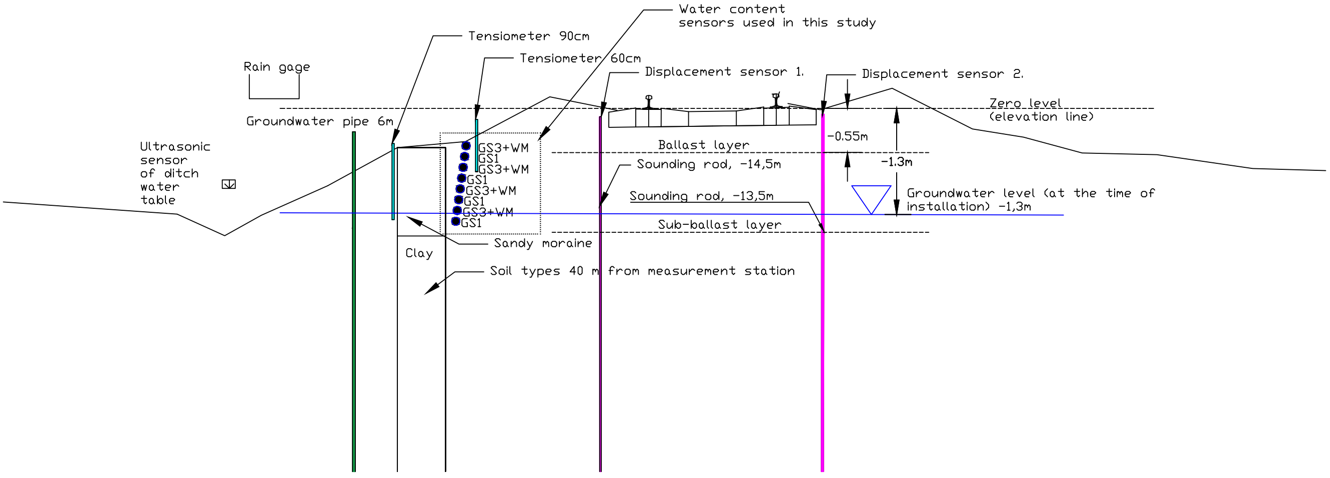

Fig. 5. An example of installed measurement instruments in track cross-section (Km 98).

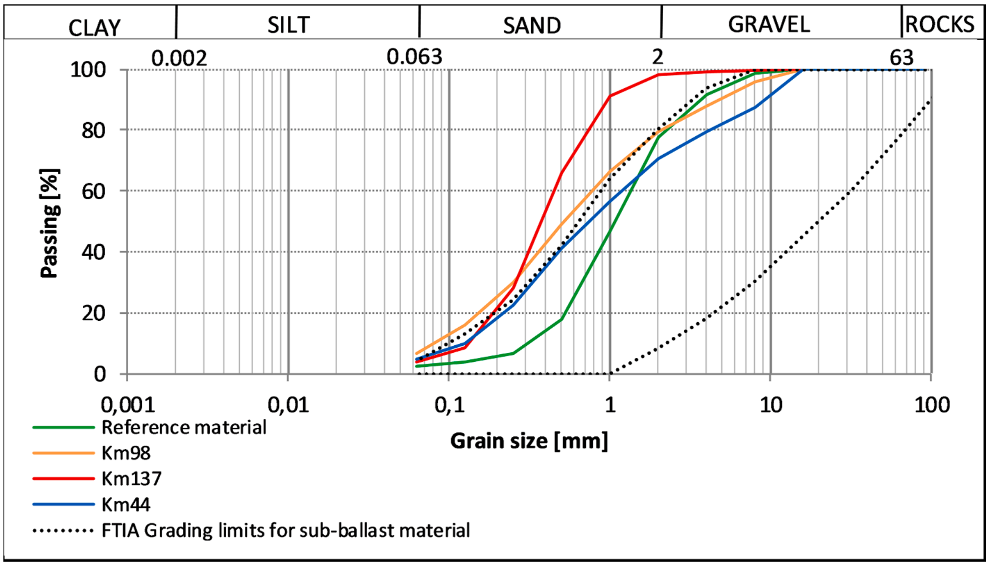

Fig. 6. The measured grain size distributions of the test materials. Dashed lines describe the grading limits of the Finnish Transport Infrastructure Agency for sub-ballast material.

Table 1
Geotechnical properties of monitoring site material samples.

Material	Particle size d_{50} [mm]	Uniformity Coefficient d_{60}/d_{10} [-]	Fines fraction content Ø less than 0.06 mm [%]	Dry density ρ_d max/ optimum water content w [g/cm^3] / [%]
Reference material 0/8	*1.1*	*4.7*	*2.5*	*1.91/2.8*
Km 44	*0.7*	*10.0*	*4.9*	*2.03 /8.5*
Km 98	*0.5*	*10.0*	*6.7*	*2.14 / 3*
Km 137	*0.4*	*3.5*	*3.7*	*1.80/ 5.9*

from site to site, so different sites cannot be compared directly to each other, but all presented results are from the sub-ballast materials monitored by sensors presented in Fig. 5. Generally, it is also good to remember that TDR soil moisture sensors can measure only the volume of liquid water. Therefore, measurement results were filtered out when the sensors were below 0 °C (white areas on the heatmap in wintertime). White areas are also caused at some other times due to sensor maloperation.

Long-term water content

Fig. 8 shows the long-term water contents of the monitoring site, Km 44. During the measurement history, before the drainage improvement at the turn of 2019 until 2020, the site experienced several periods of

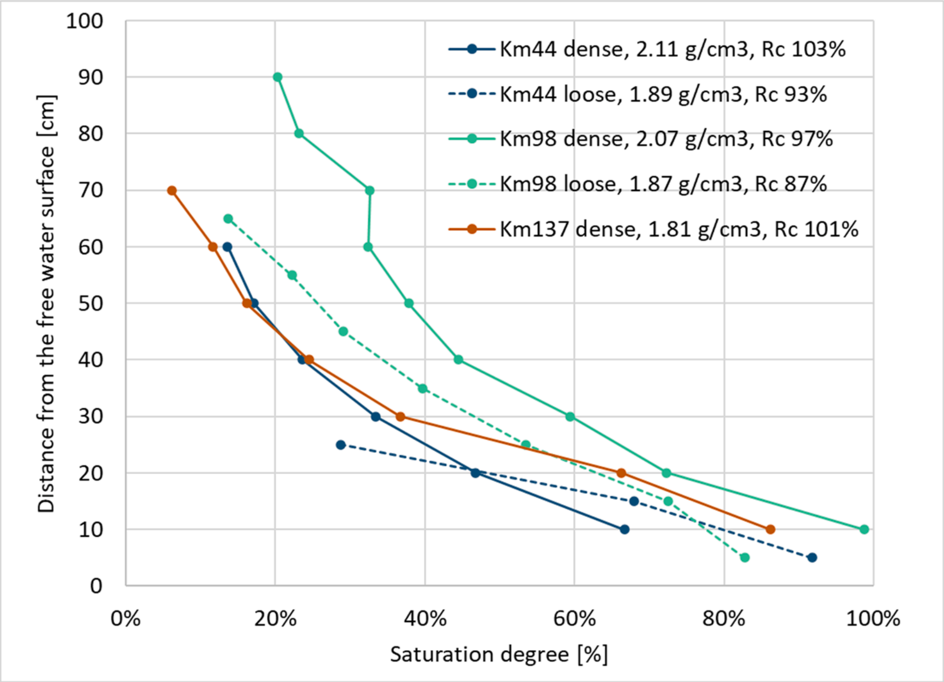

Fig. 7. Results of the height of capillary rise tests. The saturation degree decreases rapidly above the surface of the free water level.

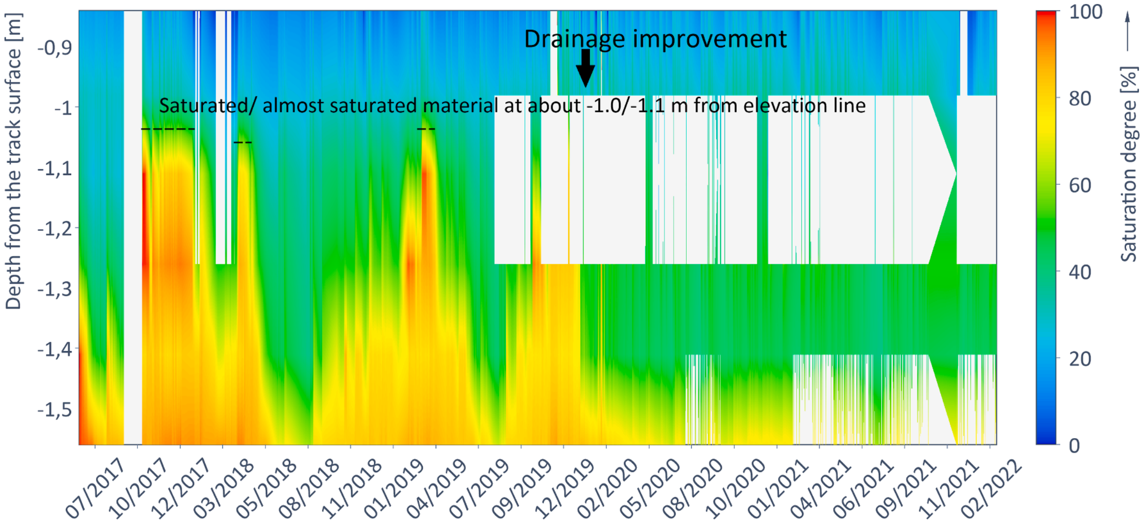

Fig. 8. The saturation degree of Km 44 sub-ballast layer. White boxes are due to intermittent malfunctions of two sensors.

high water content. The saturated zone extended to a depth of − 1,0 m from the track elevation line (zero level). These high water level moments appeared in autumn and summertime. In July 2017 and May 2018, the saturation ratio was at its lowest when the saturation ratio of the sub-ballast was approximately 50 % in the deeper structure and less than 20 % near the surface. After the drainage improvement, high water contents were no longer measured, and the saturation degree remained below 60 %. In the lowest sensor located − 1.56 m below the elevation line, there have been momentary indications of 70 %–80 % saturation degrees. Based on these measurements, the groundwater level is most likely located under the lowest sensors after the drainage improvement.

At the second monitoring site, Km 98, the water content variation cycle differed from Km 44. Fig. 9 shows the results of the long-term measurements, where the water content remained surprisingly constant during the monitoring period. In the autumns of 2017 and 2018, increased water content takes place between 1.0 m and 1.2 m below the elevation line. This can also be seen in the upper part of the sub-ballast layer, as the water content has risen to 50 %–70 % saturation degree. The variations appearing at a depth of − 1.35 m suggest that the material surrounding the sensor at a depth of − 1.2 m has better water retention capacity due to spatial variation on the layer material. The structure has also possibly dried to a saturation degree of 70 %–80 % at a depth of − 1.4 m. This drying, however, is not very clearly visible in the upper part of the sub-ballast layer, indicating clayish spots in the sub-ballast layer. The effect of rain periods is visible in the upper and lower parts of the sub-ballast layer, but the magnitude of the effects is quite modest.

Fig. 10 shows the long-term measurements of the driest measurement site, Km 137. Water content generally remained low, with less than a 60 % saturation. However, the variation in water content caused by rains is evident from time to time, which is partially explained by the good water permeability of the sub-ballast material at this site. In the sub-ballast layer, high water contents caused by the melting of frost have occurred in the spring, where the water content in the upper part of the structure has risen close to the saturated state. Fortunately, these moments have been short and mostly lasted only for a few days at a time.

Short-term water content fluctuations

In addition to the long-term seasonal water content fluctuations, short-term phenomena were also analyzed. Fig. 11 shows an example from the autumn of 2017 at Km 44, which was very rainy from September to the end of year 2017. The precipitation measured at Km 44 was 106 mm in October and almost 140 mm in November. This rainy

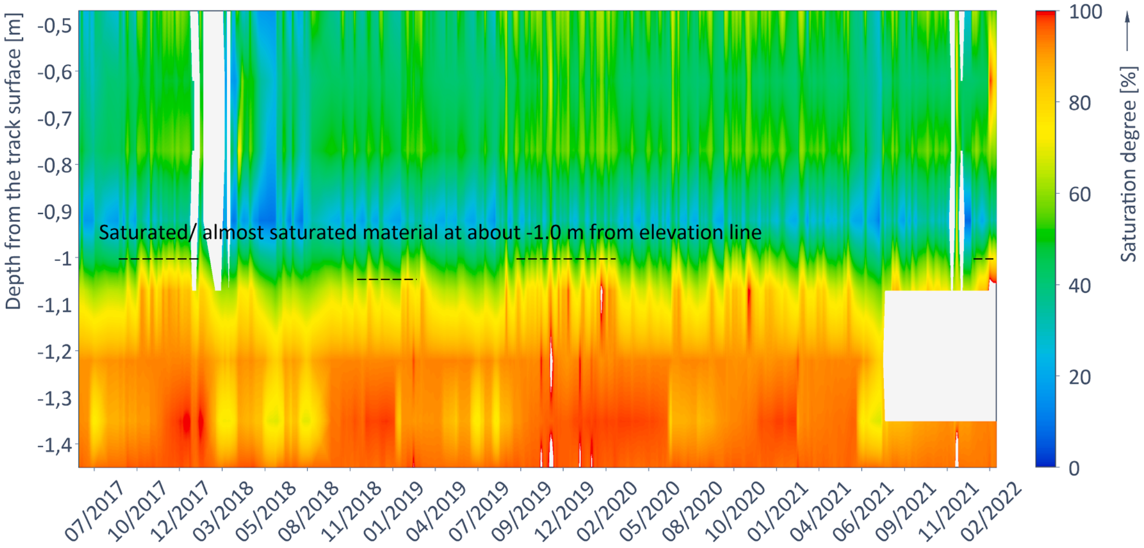

Fig. 9. The long-term saturation degrees of Km 98 sub-ballast layer. The white box is due to the malfunction of one sensor.

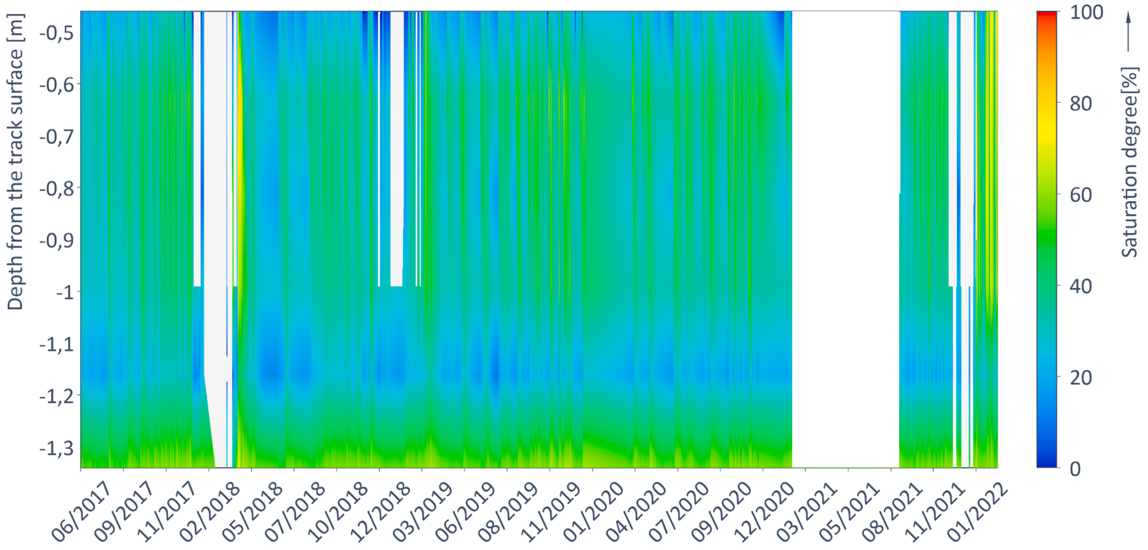

Fig. 10. The long-term saturation degrees of Km 137 sub-ballast layer. The long white area is due to the malfunction of data logger.

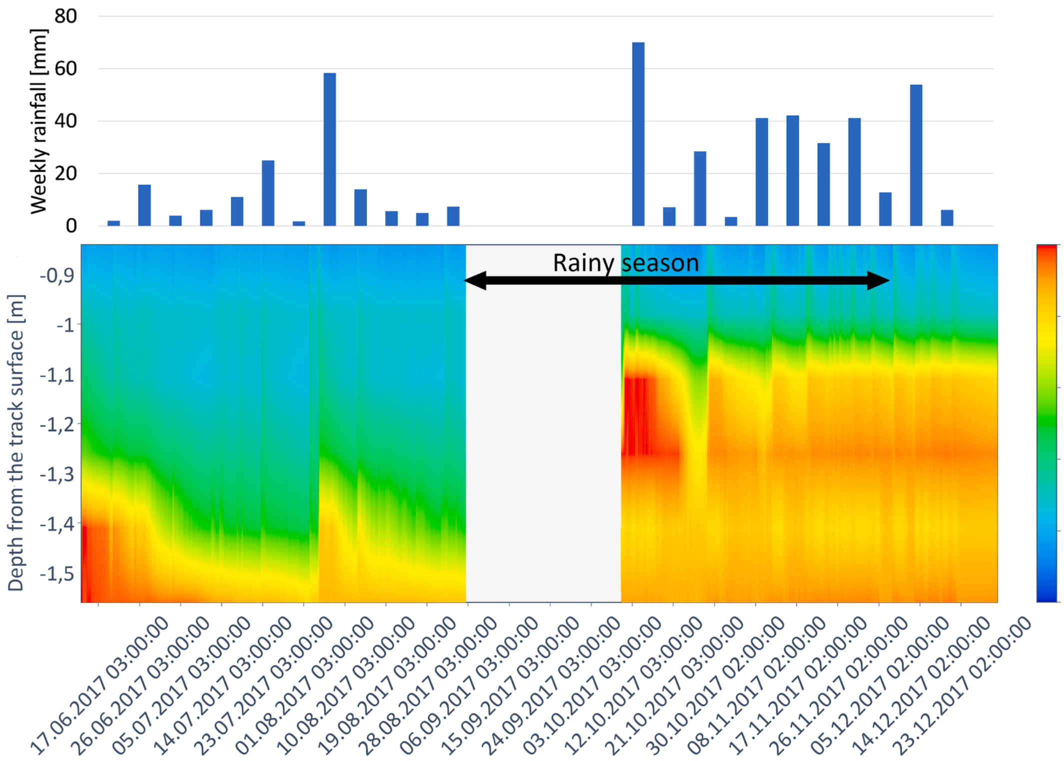

Fig. 11. Saturation degrees of Km 44 sub-ballast layer with weekly rainfalls during the summer and autumn of 2017. White area is due to total malfunction of measurement station.

season affected the water content of the upper part of the structure such that water content quickly increased from 20 to 30 % to a 50–60 % saturation degree and the practically saturated zone rose from the − 1.5 m level to the − 1.05 m level. This was due to the areal water level rather than water retained in the upper part of the structure from rains. A similar analysis was carried out for Km 98 in the autumn of 2019, and Fig. 12 shows the results. In the upper part of the sub-ballast layer, about 70 % saturation degrees have been measured to be caused by rain. Still, deeper in the sub-ballast, the surrounding water level has probably risen, which is visible in the deepest sensors' readings. The structure of Km 98 retains water better than Km 44.

Regarding Km 137, the short-term review focused on frost thawing, and Fig. 13 shows the respective measurement results. The white area at the beginning of the period was filtered out because the sensors could not measure the amount of frozen water correctly. In the spring of 2018, frost melting caused a period of approximately 80 % saturation, especially below the ballast layer, lasting for about 10 days. The water content of the rest of the sub-ballast has also increased significantly. The highest moisture contents are thus measured at the level where the increase of stresses caused by overpassing train loads is still moderately high.

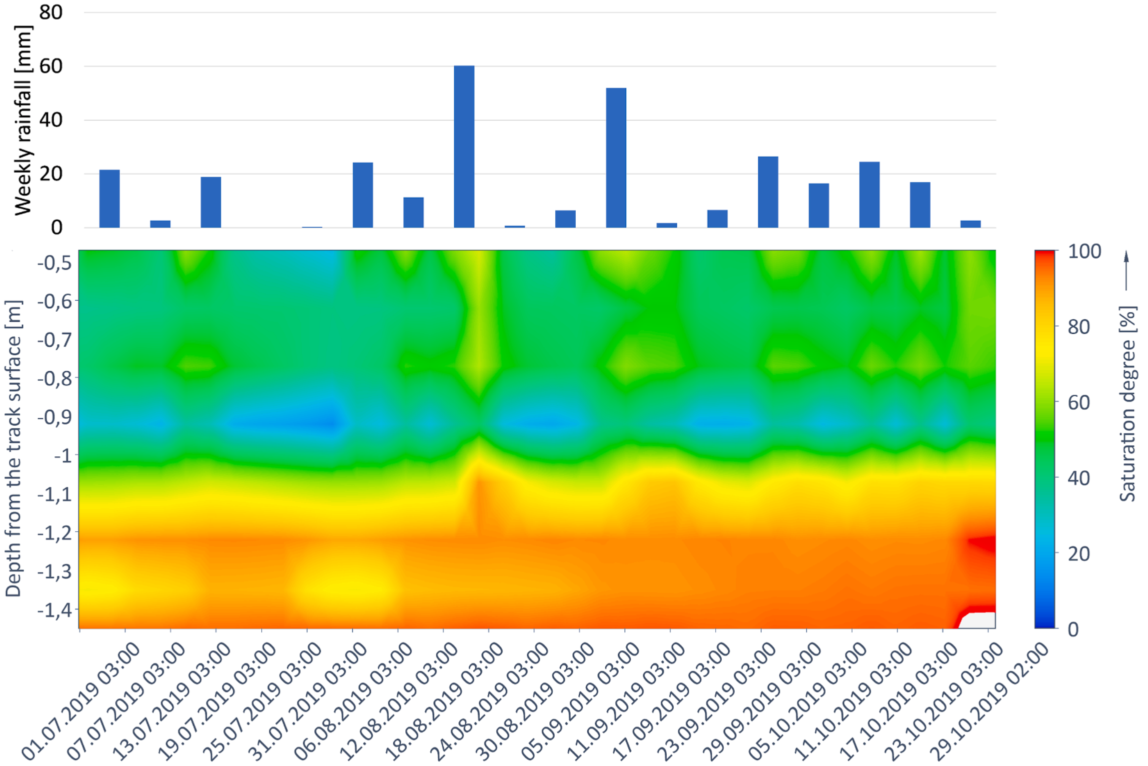

Fig. 12. Saturation degrees of Km 98 sub-ballast layer with weekly rainfalls during the rainy season of 2019.

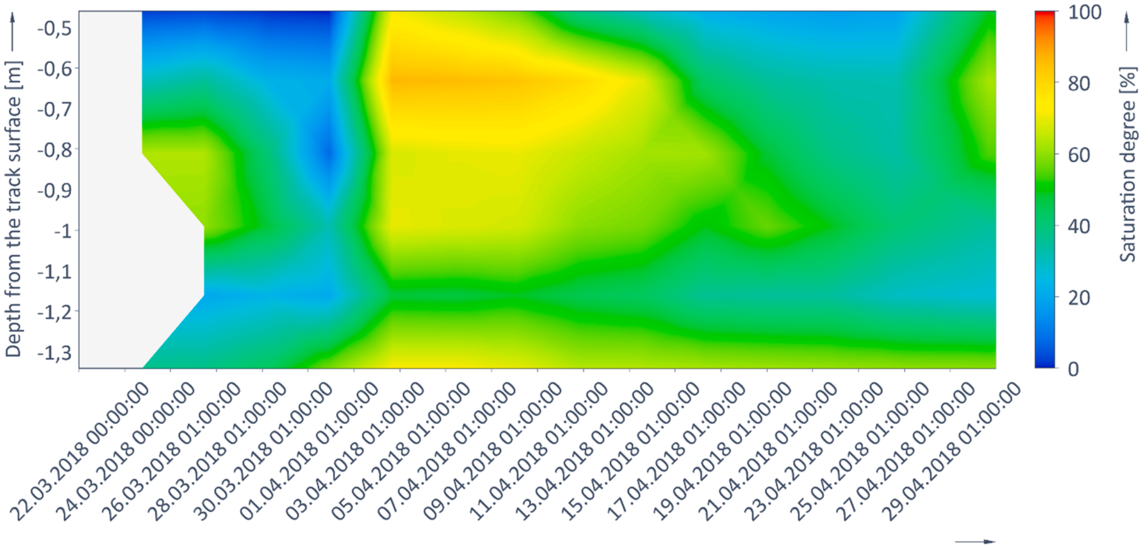

Fig. 13. Saturation degrees on Km 137 sub-ballast layer during the frost thawing period of 2018.

Discussion and conclusion

Based on the measurement results obtained from the monitoring sites, the water content of existing railway track embankments varies depending on the site, drainage conditions, and sub-ballast materials. At the minimum, 20 %–30 % saturation degrees were measured for the field sites. At the maximum, the sub-ballast layer was completely saturated up to − 1.0 m from the elevation line before the drainage improvement at Km 44. Almost completely saturated moments were also observed when the seasonal frost thawed. Predictably, water content varied according to the seasons. At monitoring site Km 44, the most intensive water content fluctuations were observed because the groundwater level was close to the sub-ballast layer of the track before the drainage improvement.

Rain increases the water content in the upper part of the track sub-ballast layer but does not bring it to a completely saturated state, even if the sub-ballast materials contain a reasonably high amount of fines (>4%). Mainly, the upper part of the sub-ballast remained at a 60 % saturation degree at highest even during the rainy season, but approximately 70 % saturation was observed momentarily at the Km 98 site. However, this is due to the silt/clay-rich zones in the sub-ballast material of Km 98, which retains water. Therefore, the water content of the upper part of the sub-ballast layer has been higher than at the other two sites throughout the measurement history. A saturated/almost saturated state detrimental to structures seems to be formed mainly due to the rise of (ground) the water level in the vicinity of the sites. This information facilitates the planning of drainage measures, as if the groundwater level will be kept at the desired level, the relatively open structure of the track does not seem to lead to particularly critical water content provided that the sub-ballast material grading is near the recommendations. However, it must be observed that the water content in this study was measured under the track shoulder, so the center of the embankment may dry slower. The almost saturated moments during the thawing period are difficult to eliminate by drainage because they are caused by melting snow and ice when the underlying structure is still partially frozen and almost impermeable.

The effect of capillary water on the sub-ballast materials of the track seems to be smaller than expected. Based on field measurements, an almost saturated capillary zone of about 10 cm appeared above the groundwater level at Km 44, where the water level has been high. In Km 98, the capillary zone has been larger, about 20–30 cm, but the water content has only been corresponding to 50 %–60 % saturation degree. Based on capillarity tests carried out in the laboratory, the degree of saturation of even low-quality materials is usually less than 70 %, around 20 cm from the free water surface. Therefore, the capillary rise would not be a problem with track sub-ballast materials classified as sand.

The drainage improvement at the monitoring site Km 44 proved to be functional. The starting point was difficult regarding site drainage, and the measurement results confirm that successful drainage improvement at a site like this is possible. The drainage improvement significantly reduced the occurrence of saturated conditions at the site, and the water content of the sub-ballast layer remained low after the improvement measures. Interestingly, also the seasonal variation disappeared almost completely, and the saturation level of the sub-ballast layer remained far from the saturated state all year round.

Significant differences in loading resistance behavior between the different sub-ballast materials were recognized in triaxial tests [17]. In the static triaxial tests, the maximum shear strength increased below a 50 % saturation degree on test site materials. This increase was due to increasing matrix suction. On the contrary, in the cyclic loading triaxial tests, differences in loading resistance were observed above 50 % saturation degrees. The different influencing methods explain this. In the static test, the matrix suction is the dominant factor, and in the cyclic tests, the development of pore water pressure decreases the loading resistance. The results of triaxial tests conducted with the test site materials led to the conclusion that over 70 % saturation degrees should be avoided on Finnish railways. However, below that, tested materials would probably work reasonably. Maintaining in-situ conditions so the saturation degree remains below 50 % to obtain the benefits of matrix suction is unlikely. Based on the water content measurements from the sites, saturation degrees lower than 70 % can be obtained by keeping the groundwater level low.

Based on this study, the following answers to the research questions can be given:

1) *The water content varies between 20 % and 100 % saturation degrees but usually stays below 70 % saturation degree above the groundwater level. The measurement data shows a surprisingly little saturated volume immediately below the ballast, although the track surface is exposed to rain. The water content in the top part of the sub-ballast layer significantly influences its loading resistance behavior. Sub-ballast materials containing lot of fines expose the track structure to maximum saturation degrees higher than 50 %. The melting of the frozen structure causes momentary, high but short-term water content.*
2) *Individual rain limitedly affects water content. In the upper part of the structure, with sub-ballast materials from Km 44 and Km 98 containing 4.9 % and 6.7 % of fine particles, rain raised the saturation level to 60 %–70 % at highest. In the monitoring sites, the most critical effect of rains is mainly a rise in the groundwater level of the area, which eventually creates a saturated state. To control the effects of rain, keeping the height of the water level under control using proper drainage methods is sufficient.*
3) *The effect of capillary rise is smaller than expected for the materials and structures studied. Significant capillary water content occurs mainly 20–30 cm above the free water surface, and the water content decreases rapidly as the distance increases from the free water surface. The water content measured in the field corresponds to those in the laboratory experiments, and the capillary rise could not create an almost saturated state with the examined materials.*
4) *At site Km 44, the drainage improvement affected the water content of the structure. After the drainage improvement, the seasonal high water content disappeared, and the sub-ballast layer was drier than before. The main impact occurred at a depth of − 1.0–1.55 m. The drainage improvement worked better than expected because the initial situation at the site was difficult.*

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CRediT authorship contribution statement

Juha Latvala: Investigation, Data curation, Writing – original draft. **Pauli Kolisoja:** Supervision. **Heikki Luomala:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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