Procedia Engineering
Volume 143, 2016, Pages 1226–1235
Advances in Transportation Geotechnics 3 . The 3rd International Conference on Transportation Geotechnics (ICTG 2016)

A Condition Assessment Approach for Highway Filter Drains Using Ground Penetrating Radar

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Abstract
The deterioration of highway filter drains (HFDs) is driven by the intrusion of foreign particles within the drainage trench. Being a porous material that offers high water removal capacity at the beginning of its service life, the drainage performance of the backfill can be significantly reduced in time by the introduced fouling material. This poses a serious safety hazard for road users (standing water on the carriageway), and can potentially have an effect in the structural capacity of the pavement. With currently limited approaches to methodically evaluate the physical condition of such assets, the Ground Penetrating Radar (GPR) offers an effective, non-destructive and continuous way to achieve this at both the project and network level. The laboratory calibration study carried out to support its adoption in a condition assessment system, builds upon the evaluation of a HFD-specific condition index aligned to permeability trials and the extraction of dielectric properties of the granular backfill material at different fouled states. The paper thus discusses what kind of HFD distress information are to be collected (condition data) and how this can be achieved (data collection methods), and defines four distinctive HFD media condition bands (Excellent to Very Poor) based on the proposed free voids ratio (R_{FV}) ranges and extracted relative permittivity values.

Keywords: Highway Filter Drains, Ground Penetrating Radar, Condition Assessment, Permeability, Fouling Index

1 Introduction

The deterioration of highway filter drains (HFDs) is driven by the intrusion of foreign particles within the drainage trench. Being a porous material that offers high water removal capacity at the beginning of its service life, the long run performance of the backfill can be severely reduced by the introduced fouling material. This manifests as a serious safety hazard for road users (standing water on the carriageway), and can potentially have an effect on the structural capacity of the pavement.

With no formal frameworks currently in place to allow the assessment of the physical condition of in - service HFD and thus to enable holistic management of the drains, this paper investigates the condition data required and the means to collect them in order to support proactive and condition-

 Selection and peer-review under responsibility of the Scientific Programme Committee of ICTG 2016

doi:10.1016/j.proeng.2016.06.108

driven HFD management. The aim of this work is to present a quantitative metric that can be used to assess the physical condition of HFDs and the tools being developed to enable the collection the aforementioned metric (or distress scale).

A laboratory-based evaluation of the HFD deterioration characteristics is hence described building upon large scale permeability trials (linking the proposed fouling metric to anticipated levels of drainage capacity) and the use of a non-destructive evaluation technology (namely the Ground Penetrating Radar - GPR) to introduce the means for a network level condition evaluation approach. The combination of the two experimental studies addresses the deterioration of HFDs and aims to define condition data collection and particularly:

- What is to be measured.
- How can this be measured?

2 Background

2.1 HFD Function, Deterioration and Condition Assessment Principles; Defining the Basis for Engineered Maintenance Planning

Highway filter drains are aggregate filled trenches fitted with a porous carrier pipe at the base used to drain significant lengths of the UK highways network. The granular material used, which is typically (but not restrictively) exposed at the surface of the trench, allows for efficient removal of pavement run-off due to its high porosity. It also enables the removal of subsurface water from the pavement foundation and structural layers. Such (combined) systems can be advantageously employed in cuttings, which require significant ground water removal. The drains are constructed in verges and/or central reserves adjacent to the low edges of pavements enabling surface water to run off the pavement directly onto the trench and then permeate through the aggregate backfill to the drainpipe at the base of the drain.

The deterioration of the particular drainage asset is caused by the accumulation of introduced particles (fouling material) within the filter media during its operational life. A number of studies have been conducted in the past to address deterioration of such drains but these often provide information related to the fouling composition found in trenches without really addressing the question of managing maintenance operations and defining condition assessment principles (Samuel & Farrar, 1989; Samuel & Farrar, 1988). Current design-life projections suggest the aggregate fill will reach a poor state after 10 years of operation requiring replacement at that point.

From site observations and empirical understanding of the asset's long-term performance, if introduced fines fill up the available void space in a trench, the drainage capacity of the material may drop significantly. Depending on the progression of this type of deterioration and the concentration of fouling at either the uppermost or basal sections of a HFD, two distinctive failure modes can be identified. The first, more related to the surface-water removal capacity, manifests when a cohesive and often impermeable (when compared to the initially free draining backfill) crust forms at the surface of the trench which limits the free flow of runoff from the carriageway down the trench. Water is re-directed back to the pavement surface resulting in 'spray' and potentially wet-skidding accidents attributed to hydroplaning (Black & Jackson, 2000).

It is widely recognised that the presence of excess moisture in pavement layers can reduce the structure's service life. Deteriorated HFDs may be unable to cope with rising groundwater tables and allow water to reach the pavement subgrade from various sources (pavement edge, surface discontinuities, water table, and high ground). The second failure mode related to a gradual 'bottom-up' deterioration of the fill may lead to a HFD section that fails to remove sub-surface water and surface runoff from the pavement system and thus reduce the structural capacity of the courses affected. Excess water may lead to a number of failure modes and road engineers usually aim to reduce water problems by eliminating water infiltration (through the wearing courses) and to design drainage systems that enable quick removal of water from the structure.

If fouling levels as a direct measurement of HFD deterioration can be linked to performance levels, a condition evaluation framework accountable for the asset's degradation characteristics can be established (Stylianides, et al., 2015a.). The methods of collecting the condition data should then be addressed in a way that reinforces asset management (AM) principles and allows the identification of drainage assets that offer low levels of service, the subsequent determination of the maintenance backlog and the definition of intervention planning and treatment options.

With conventional HFD condition assessment thinking (and lacking any official evaluation framework) data for condition evaluation can be obtained from predetermined test sections or through visual inspections. Both means will fail to address fouling levels and hence deterioration extent in a quantitative manner. The former option will inevitably enable only discrete data evaluation (for an asset that usually spans over many kilometres), or costly and time demanding sample collection and sieving / sorting. The latter is based on rating rather than measuring, and bound to provide subjective results (Stylianides, et al., 2015b.). Since no holistic condition assessment approach has been proposed to date, the adoption of a non-destructive testing / evaluation (NDT) technology that has the advantage of rapid and continuous assessment of linear assets is proposed and presented in the following sections.

2.2 GPR Fundamentals; Pavement and Railway Applications

A NDT option that has been adopted in various highways and transportation related condition surveys and is being supported by a vast number of pavement (Evans, et al., 2008) and ballast (Leng & Al-Qadi, 2009; De Chiara, et al., 2014; Al-Qadi, et al., 2010; Kashani, et al., 2015) laboratory or field studies, is the GPR. Elements of the supporting literature (and of the current practice), pertaining to the evaluation of layer thicknesses in pavements or the identification of spent ballast in railways studies using this technology, show potential in respect to identifying and proposing a condition data collection methodology for HFD ad-hoc conditions.

The GPR is a sub-surface sensing technology introduced in the early 1970's used for both shallow and deep investigations and has since grown in use in the highways and railway sectors. Three electrical properties pertaining to material characteristics govern the propagation, attenuation and scattering/reflection of the electromagnetic pulse through a medium, namely magnetic susceptibility (or permeability) - (μ), electrical conductivity (σ) and lastly relative permittivity (ϵ). Interchanging electrical properties within an evaluated medium cause significant reflection events of the incident wave. As the electromagnetic pulse is radiated from the GPR, it travels vertically through the medium under evaluation at a velocity (u) which is primarily a function of the permittivity value (and of the speed of light in vacuum $c = 0.3\ m/ns$) according to:

$$u = \frac{c}{\sqrt{\epsilon}} \quad (1)$$

The wave spreads out and travels downwards until it reaches an object (or a stratigraphic layer) that has different electrical properties than the host layer, at which point the wave is reflected and evidence of its reflection is detected by the receiver. Such differences can be a result of moisture or density variations or even the presence of a different material in the evaluated section (i.e. a wave propagating through a dry gravel layer through to a wet sand layer) (Daniels, 2000). The amount of energy reflected will be a function of the reflection coefficient γ, which is defined according to:

$$\boldsymbol{\gamma} = \frac{\sqrt{\boldsymbol{\epsilon_2}} - \sqrt{\boldsymbol{\epsilon_1}}}{\sqrt{\boldsymbol{\epsilon_2}} + \sqrt{\boldsymbol{\epsilon_1}}} \tag{2}$$

where ϵ_1, ϵ_2 correspond to the dielectric constants of the material the wave is exiting from and the one it is entering to respectively. As a result, reflected energy will reach the receiver at different times as a function of the dielectric constant of the materials met in the EM wave propagation path. The amplitudes are then recorded and plotted as a function of time (or depth if the dielectric constant can be measured or estimated) and a GPR trace is generated.

The most common property evaluated in practical applications of the GPR (in both pavement and railway track-bed investigations) is the relative permittivity (ϵ) or 'dielectric constant' (κ) as is often referred to in literature. The permittivity of subsurface materials may vary dramatically, especially in the presence of free water ($\epsilon_{air} = 1$, $\epsilon_{granite(dry)} = 5$, $\epsilon_{clay} = 5 - 40$, $\epsilon_{water} = 81$ (Saarenketo, 2006)). If the thickness of the evaluated medium is known or easily identified with practical means, information regarding the intrusion of fines (in a ballast layer) or water (in ballast / pavement) in the same medium can be extracted. This is particularly important in railway condition surveys as the measured relative permittivity is often used to infer a level of ballast fouling (extent and level of deterioration of the section) and 'engineer' the maintenance planning process. In general, higher values of measured ϵ are indicative of increased levels of ballast deterioration (Leng & Al-Qadi, 2009); for pavements, steep increases or discontinuities of the same value may suggest the presence of excess water in the pavement system or foundations (Benedetto & Pensa, 2007). The other way around, if the dielectric constant of a specific material is known, the thickness of a layer (r) comprised of this same material, can easily be calculated based on the signal's two-way travel time (Δt) using

$$r = \frac{(u \times \Delta t)}{2} = \frac{c \times \Delta t}{2\sqrt{\epsilon_r}} \tag{3}$$

3 Methodology

The following methodology describes the condition metric devised for ad-hoc HFD design and deterioration characteristics, and the means to evaluate it non-destructively. The condition assessment approach builds upon two discrete pillars: the adoption of condition indices aligned to permeability trials (the means to assess the physical condition and infer a level of performance) and the extraction of relative permittivity values of the granular backfill material using a ground coupled 1GHz antenna (the tool used to carry out the condition assessment).

3.1 What to Measure; Fouling Scales and Drainage Capacity

The large-scale permeameter (seen in Figure 1) allows for the measurement of hydraulic conductivity values of samples with a radius of 375mm and depth of 450mm with varying fouling levels under a relatively low constant head. Vertical hydraulic conductivity values (k_v) of different aggregate-foulant mixes are extracted and are used to simulate and define discrete condition states representative of fouling levels mapped to an anticipated level of drainage performance. k_v values are then normalised using an assumed $k_{vmax} = 50\ mm/sec$ (this extracted by considering the non-linear increase of k_v with decreasing levels of fouling and the maximum recorded $k_v \approx 39\ mm/sec$ at low levels of fouling– see Figure 4). Water is initially used to fill up the tank and measurements of flow are completed once samples are fully saturated. A constant flow is achieved using a weir at the top of the tank and the permeability at each fouling state is extracted by measuring the trial time and flow for each test and adopting Darcy's Law.

The filter material used is Type B (BSI specifications) aggregate (or 20-40mm stone as commonly referred to), and the fouling mix is designed in such a way as to represent the fouling retrieved from site evaluations conducted in the past (Stylianides, et al., 2015a.). The index used to represent the

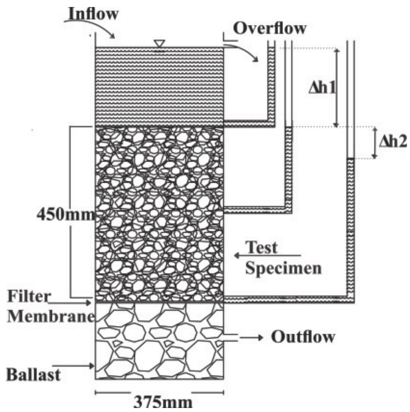

Figure 1: Schematic of large-scale permeability tank used in laboratory trials

changing status of the aggregate fill in the study is a volumetric index formulated adopting simplistic material properties and normalising the data according to the filter's 'fresh' available void space. This (the free voids ratio, R_{FV}), is a further development to the metrics presented in Stylianides, et al., (2015a.) and modified to better represent the deteriorated backfill aligned to the particle matrix anticipated to have an effect in the vertical permeability (k_v) of the evaluated aggregate-fouling mix. While limited field evaluation studies have been (to date) presented targeting HFD deterioration, defining a distress index can be achieved by building upon relevant ballast evaluation studies

(Indraratna, et al., 2011; Anbazhagan, et al., 2012) and adopting basic engineering judgment. The particle matrix comprised by the fouling mix below 8mm is thus selected to represent the introduced material in trenches (fouling). The formula used to represent the index 'Free Voids Ratio' in this case is:

$$R_{FV} = \frac{V_{VFRA} - V_F}{V_{VFRA}} = \frac{e_{fr}V_A - \frac{M_F}{\rho_f}}{e_{fr}V_A} = \frac{e_{fr}\frac{M_A}{G_A} - \frac{M_F}{\rho_f}}{e_{fr}\frac{M_A}{G_A}} \quad (4)$$

V_{VFRA} is an estimation of the volume of voids in a fresh backfill while V_F represents the volume of the fouling material. The former is calculated using e_{fr}, the void ratio for fresh Type B aggregate, adopted here to be equal to 0.65. This value can range between 0.6 and 0.8 as extracted in laboratory trials and for in-situ evaluations it will depend on the particular gradation characteristics of the HFD backfill used and the levels of compaction achieved (Type B material is defined using a gradation envelope in design standards thus minor deviations from the proposed e_{fr} are anticipated). The material's specific gravity G_A is again extracted in the laboratory while ρ_f, defining the bulk density of the foulant, is meausured to be equal to 1.5 tons/m^3. This value has been derived using the engineered fouling material used in this study and a number of compaction tests. In simple terms, Equation 3 represents a normalised estimation of the available void space in a HFD medium and can be accountable for condition information extraction as seen in the experimental trials section below.

3.2 How to Measure it; Non-Destructive Evaluation and Dielectric Dispersion Study

For this set of trials, a $0.5 \times 0.5 \times 0.5m$ container is used to extract dielectric permittivity values by evaluating propagation velocities between known interfaces in the signal's time domain. To distinguish between the required interfaces, a perfect reflector (steel plate) is positioned at the bottom-end of the tank. Figure 2 exhibits the general setup, the ground-coupled EkkoPulse GPR used for this

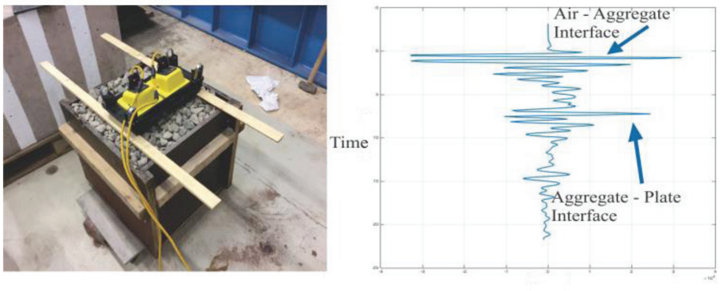

Figure 2: Container, 1GHz EkkoPulse antenna and typical unprocessed A-scan

set of trials and a time-domain waveform that depicts typical material boundaries in a NDT trial. The container is built using nominal metallic elements to minimise any interference or noise in the extracted and processed A-scans.

Three types of fouling material are adopted here; a clay and a sand based, and an engineered foulant (CF, SF, EF respectively), to match in-situ fouling conditions. The aim of this element of the work, is to study how the dielectric constant can be extracted and highlighted for materials with different fouling and moisture levels that may replicate in-service deteriorated HFD sections. The GPR used in the study is a ground-coupled system with an antenna of 1GHz central frequency.

The tank is initially filled with the aggregate material simulating a 'fresh' fill. Once data collection is completed for a particular aggregate-fouling trial, fouling material (sand or clay or the combination of the two) is introduced in the container and mixed in the aggregate sample using a pneumatic drill to change the fouling status of the following trial. Material interfaces are identified using a time-domain waveform and the dielectric permittivity values are calculated based on the fill's depth and the wave's two-way travel time (Δt [ns]) using Equations (1) and (3). Permittivity values are also extracted at different moisture content levels at fresh and highly fouled states using the available foulants. To achieve this, water is added in the tank and allowed to evaporate naturally; gravimetric water content (GWC) is then measured for each sample.

4 Results

4.1 Condition Metrics and Drainage Capacity

By linking the proposed fouling index to the physical condition of the HFD backfill, a swift evaluation of conditions can be extracted (see Figure 3). In this method, a handful of simple properties of the filter media aggregate and foulants require measuring. The approach is practical and pragmatic and is in fact the first quantitative approach in classifying and evaluating the deterioration characteristics of the aggregate backfill. Using R_{FV}, one can draw conclusions regarding the drainage performance of the HFD backfill and establish discrete asset condition bands if the index is then mapped to a series of permeability trials to measure the anticipated drainage performance drop.

Figure 3 Representation of 3 fouling states using $\boldsymbol{R_{FV} = 100\%}$, $\boldsymbol{R_{FV} = 50\%}$ **and** $\boldsymbol{R_{FV} = 0\%}$**:**

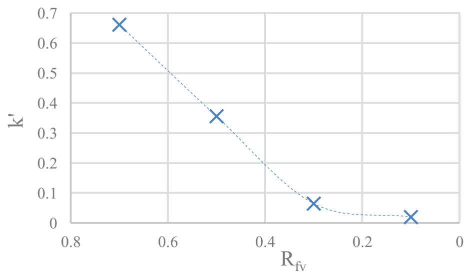

Figure 4: Variation of normalised permeability as a function of $\boldsymbol{R_{FV}}$

Figure 4 presents this illustrating the normalised vertical permeability value of the fill ($k' = k_v/K_{vmax}$), extracted as a function of the free-voids ratio. Below $R_{FV} = 0.3$, it can be assumed that the material becomes foulant - dominated and presents extremely low (normalised) permeability values; in principle this will result in low levels of performance and will be indicative of a HFD section that can be considered as 'spent'. While for in-service conditions there will be a number of parameters to factorise when drainage performance of a pavement section is considered, the vertical hydraulic capacity of the aggregate fill can be used to predict the anticipated 'drainage efficiency' of a particular HFD trench.

4.2 GPR Calibration Study

The electrical alterations caused by introducing sand, clay and the engineered fouling material along with moisture within the trial tank, cause distinctive reflection and propagation variations that are easily identified in a typical time-domain waveform. Material boundaries can easily be extracted (as seen at Figure 2), due to the anticipated large peaks at air - aggregate and aggregate - steel plate interfaces, using simple post-processing filtering (time-zero correction and bandpass butterworth within the time domain). Figure 5 exhibits how ϵ varies as a function of fouling types and levels. The use of clay fouling results in higher permittivity values and in general terms, a reduced R_{FV} results in lower wave propagation velocities in the evaluated medium and thus higher extracted values of ϵ.

Moisture content plays a significant role in the GPR calibration study. Figure 5 also presents permittivity values as a function of water content for samples with different fouling conditions. It is clear that with increasing moisture levels, the permittivity values of the aggregate-foulant mix shift to much higher levels even in cases of generally low fouling content. At GWC= 3% and $R_{FV} = 70\%$,

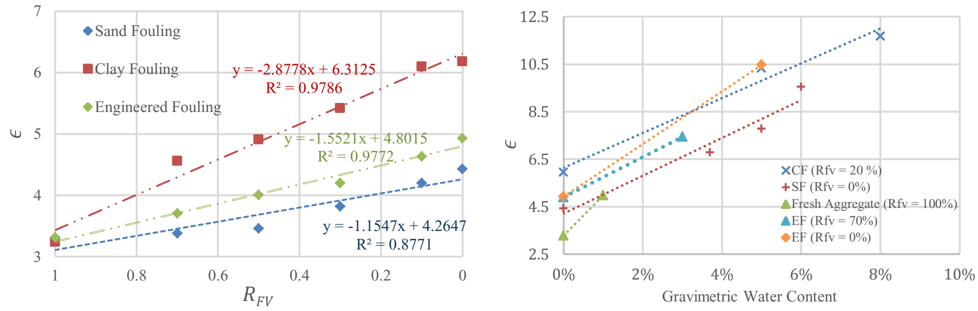

Figure 5: Variation of dielectric permittivity as a function of $\boldsymbol{R_{FV}}$ and as a function of different water content levels

using the engineered fouling material, $\epsilon = 7.43$. At $R_{FV} = 0\%$ for a dry, sand-fouled sample $\epsilon = 4.42$; the value moves up to $\epsilon = 9.54$ for $GWC = 6\%$ for the same type and extent of fouling.

It can be generalised that high extracted permittivity values during a condition survey can be attributed to a combination of fouling levels and moisture content. With increasing clay content in the fouling mix, the parameter gets even larger but the data suggests that the wave velocity is more sensitive to moisture rather than fouling levels (or types). The highest extracted permittivity $\epsilon = 11.67$, occurs at $R_{FV} = 20\%$ using clay fouling and an extracted gravimetric water content of 0.08. Compared to fresh aggregate ($\epsilon_{fresh} = 3.28$) this is the largest deviation of relative permittivity recorded in this study even though higher values should in principle be extracted with increasing levels of moisture or fouling in a HFD trench.

5 Conclusions

A laboratory study has been conducted to introduce a condition assessment methodology for the aggregate backfill of HFD. The study revolves around two main axes: the identification of relevant condition data, and the introduction of a non-destructive method to collect this data. The paper thus presents the alignment of a proposed distress classification index, R_{FV} as a normalised volumetric quantification of foreign material in a trench, to a level of anticipated performance ($k' = k_v/k_{vmax}$), as a measurement of normalised vertical permeability of the aggregate fill and then to a range of dielectric constants for aggregate fills at varying condition states. It is shown how the hydraulic permeability of the aggregate backfill reduces with increasing fouling levels ranging from a normalised value of 0.67 to one of 0.02 for a range of R_{FV} [0.7 0.1].

Table 1 brings the fouling index, performance levels and dielectric evaluation information together (focusing on ϵ for dry conditions), and offers a classification approach with four condition bands that range from excellent, to spent aggregate fill. This should address the two main questions raised in Section 1 (what to measure and how to measure it).

The permittivity dispersion study suggests that water will be the parameter that defines the propagation velocity of the radio-waves in the filter medium and it cannot be ignored in a condition evaluation study. In fact, while water content can be loosely linked with fouling levels (in general terms, higher fouling levels can be indicative of higher levels of retained water and vice-versa) this won't always be the case on site. Fouling-free, wet aggregate for example, can have a significantly larger permittivity value than in its dry state ($\epsilon_{aggwet} = 4.97$ - $\epsilon_{aggdry} = 3.28$) and as such, a trench could falsely be identified as highly fouled or spent. In brief, condition surveys completed in wet periods can lead to false results and unnecessary maintenance planning if the causes for the decreased wave propagation velocities in the filter medium are not properly identified and taken into account. It

Condition Band	R_{FV}	$k' = \frac{K_V}{K_{max}}$	ϵ dry
As new - Excellent	$R_{FV} > 0.7$	$k' > 0.6$	$\epsilon < 3.7$
Good	$0.7 < R_{FV} > 0.5$	$0.6 < k' > 0.35$	$3.7 < \epsilon > 4$
Poor	$0.5 < R_{FV} > 0.3$	$0.35 < k' > 0.05$	$4 < \epsilon > 4.2$
Very Poor - Spent	$R_{FV} < 0.3$	$k' < 0.05$	$\epsilon > 4.2$

Table 1: Setting discrete condition bands and linking $\boldsymbol{R_{FV}}$ to $\boldsymbol{K_V}$ and $\boldsymbol{\epsilon}$.

might thus be reasonable to target HFD condition surveys during dry periods and calibrate the GPR response by extracting targeted samples from drainage trenches to correlate also for moisture content in the drainage trench.

A linear relation can be extracted from the presented figures linking the incremental increase of ϵ as a function of R_{FV} but further validation and calibration of the GPR data collection method and processing techniques is required before full-scale condition surveys can be undertaken. Further work packages planned include elements of additional testing and data processing (employing evaluation approaches based on analysis from void scattering and the frequency domain) to enable enhancement of the condition data collection method.

Acknowledgements

The research work described in this paper has been funded by the Engineering and Physical Sciences Research Council (EPSRC) via the CICE at Loughborough University, Transport Scotland (TS) and Balfour Beatty. The opinions and findings are those of the authors and do not necessarily represent the views of TS.

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