Tailings Dam Reservoir Sectoring Using CPTU and Geophysical Test Data

Amanda Souza(✉), Bruno Novais, Michel Fontes, and Naiala Fidelis

Fonntes Geotecnica, Belo Horizonte, Brazil
amanda.almeida@fonntesgeotecnica.com

Abstract. The need for stabilization of a dam located at Quadrilatero Ferrifero, located at the Southern of Craton São Francisco, in Brazil, demanded geological-geotechnical studies that made possible the building of a geological model that reflects the behavior and distribution of sediments deposited within the reservoir. The structure was built in an embedded valley, on residual shale soil and, more locally, over a layer of iron ore tailings between 8.0 and 9.0 m thick.

To develop the model, boreholes were drilled to identify and characterize the material within the reservoir and CPTU tests were performed to obtain the geotechnical behavior of the materials. Based on these investigations, it was possible to establish a sectorization of the tailings within the reservoir, allowing a more reliable assessment of the dam's stability and identifying the regions vulnerable to liquefaction. The different tailings groups would have been deposited in a similar way to the deposition of sediments, described by the Krubein and Sloss sequence stratigraphy theory in 1963.

The integration of the results of the electroresistivity geophysical surveys with the geological-geotechnical sections assisted the elaboration of the proposed geological model. The geophysical data indicated the possible regions where the tailings would be saturated, favoring water. The areas that presented lower resistivities coincide with the areas where the CPTU tests indicated the presence of a tailings with clayey behavior (saturated) and the areas of more sandy tailings coincide with the regions of intermediate resistivity.

Keywords: Tailings Dam Sectoring · CPTU tests · Quadrilatero Ferrifero

1 Introduction

The present work consists of a series of geological and geological-geotechnical investigations in order to determine the behavior and distribution of the iron ore tailings inside the dam. This tailings distribution follows the concept of sequence stratigraphy, proposed by Krumbein and Sloss in 1963. This fact can be verified in the field through the stratigraphy revealed by the 62 boreholes and the behavior observed in the 22 CPTU tests performed in the reservoir region.

Robertson's (2010) criteria for CPTU tests were created based on tip strength (Eq. 1) and friction ratio (Eq. 3), both normalized.

$$Q_{tn} = \left[\frac{(q_t - \sigma_{v0})}{p_a}\right]\left(\frac{p_a}{\sigma'_{v0}}\right)^n \tag{1}$$

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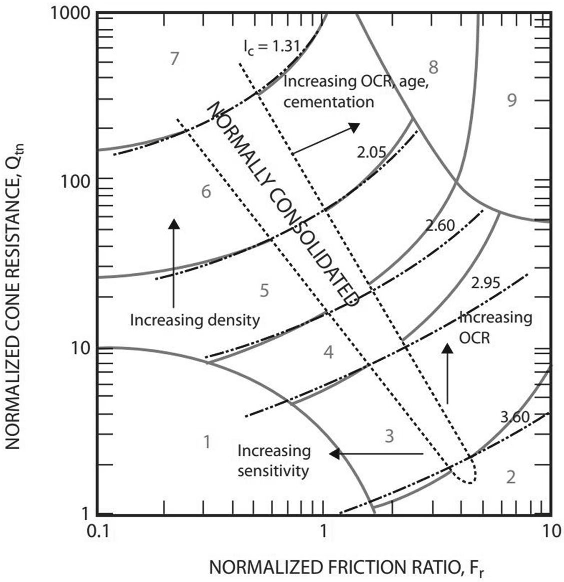

Fig. 1. Standard abacus SBTn Qt – Fr, Robertson (2010).

where $\frac{(q_t - \sigma_{v0})}{p_a}$ is the dimensionless tip resistance; $\left(\frac{p_a}{\sigma'_{v0}}\right)^n$ is the stress normalization factor, p_a is the atmospheric pressure in the same unit as q_t, σ_{v0} and σ'_{v0}, n is the variable stress exponent as a function of SBTn, this is defined by Eq. 2.

$$n = 0,381(I_c) + 0,05\left(\frac{\sigma'_{v0}}{p_a}\right) - 0,15 \tag{2}$$

The soil classification chart used in the study is obtained from the abacus suggested by Robertson (2010), Fig. 1, and the relation between the normalized tip resistance and the friction ratio also normalized (Fr), Eq. 3.

$$F_r = \left[\frac{f_s}{(q_t - \sigma'_{v0})}\right]\left(\frac{p_a}{\sigma'_{v0}}\right)^n \tag{3}$$

where $\frac{f_s}{\left(q_t - \sigma'_{v0}\right)}$ is the dimensionless lateral friction, $\left(\frac{p_a}{\sigma'_{v0}}\right)^n$ is the stress normalization factor; p_a is the atmospheric pressure in the same unit as q, σ_{v0} and σ'_{v0}, n is the variable stress exponent as a function of SBTn, this is defined by Eq. 2. Being f_s is the lateral friction and q_t is the tip resistance obtained from the CPTu test, σ_{v0} is the total vertical stress and $\sigma'_{v0} = \sigma_{v0} - u_0$ is the effective vertical stress.

2 Methodology

To develop the geological-geotechnical model of the dam reservoir, information obtained in the investigation campaigns executed in the area was used.

Comparisons were made between the information on the drilling LOGs and the photos of the respective core samples, in order to confirm the contacts between the different units described. Then, the interpretation of the CPTU test results was performed using Robertson's (2010) methodology, which classifies the materials into different textures according to their behavior during the test.

The original topography (before the construction of the Dam) was used to mark the contact between the tailings and the foundation in areas where there was no information from boreholes or CPTU. When divergence was observed between the contact information brought by the direct geological-geotechnical investigation and the original topography, the former was adopted.

Finally, the geological-geotechnical sections constructed based on the boreholes and the CPTU tests were confronted with data from geophysical electroresistivity surveys, as a way of validating the model generated.

3 Regional Geology

The dam under study is inserted in the geological context of the Quadrilatero Ferrifero (Dorr 1969), a polymetallic province of approximately 7000 km^2 located at the southern of the São Francisco Craton, in the central portion of the state of Minas Gerais. It consists of a geological structure compartmentalized in two large supergroups: the Nova Lima Supergroup (base), representative of an Archean greenstone belt; and the Minas Supergroup (top), formed by Paleoproterozoic metasedimentary rocks (Fig. 2). Both supergroups were deformed by the Transamazonian (2.1–2.0 Ga) and Brasiliano (0.65–0.50) orogens.

The target structure of the studies is located in the geological domain of the Rio da Velhas Supergroup (Dorr 1969), in an area described as being formed by chlorite-quartz schist, calciosilicate rocks and carbonaceous metargillite.

4 Local Geology

The dam reservoir is predominantly located over a residual shale soil horizon, as well as locally over a tailings layer approximately 8 to 9 m thick located in the region of the former main stream channel.

The residual soil horizon, developed from weathering and pedogenesis processes of metavolcanosedimentary rocks, presents, in general, a silty-sandy texture, reddish to yellowish colors with white hues, conspicuous planar structuring, compactness ranging from medium to compact, as well as thickness ranging from 2 m to 4 m.

Over the residual soil, in some regions, a layer of thallus about 2 m thick occurs, characterized by having a sandy-thin matrix with silt, a reddish-brown color, as well as predominantly tabular and prismatic shale fragments in the fine to coarse gravel, block and, eventually, boulder fractions.

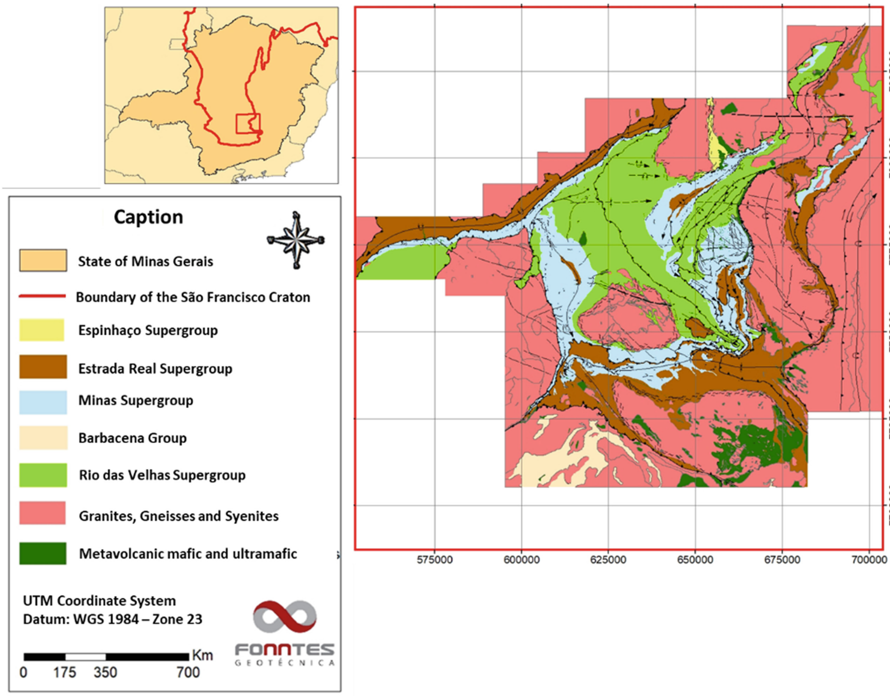

Fig. 2. Regional geological map of the Iron Quadrangle, modified from Endo et al. 2019.

Below the residual soil level occurs the saprolite horizon of the shale, characterized by exhibiting yellowish to reddish colors, whitish hues, a silty-sandy to silty texture, conspicuous planes of anisotropy, as well as about 3 m to 6 m thick.

Beneath the saprolite horizon is the whitish gray, altered to moderately altered, highly fractured, very soft to medium strength shale containing sloping to sub-horizontal joints.

The reservoir, in turn, is composed of iron ore tailings characterized by exhibiting a reddish brown to dark gray color. The concatenation of the information obtained from the boreholes and the CPTU's allowed to discretize the tailings into 4 groups according to the geotechnical behavior obtained from the SBTn graph generated based on Robertson's criteria (2010), namely:

a) Type 1 Tailing: Presents a predominantly silty clay texture with intercalations of a sandy silt texture;
b) Type 2 Tailing: Presents a predominantly sandy silt texture with intercalations of a silty clay texture;
c) Type 3 Tailing: Presents, in general, a stratified pattern given by the alternation of silty sand and sandy silt layers. As for the geotechnical aspects, it stands out for presenting drained behavior interrupted occasionally by stretches with undrained behavior given by the pore pressure generation peaks;
d) Type 4 Tailing: Presents a predominantly sandy texture.

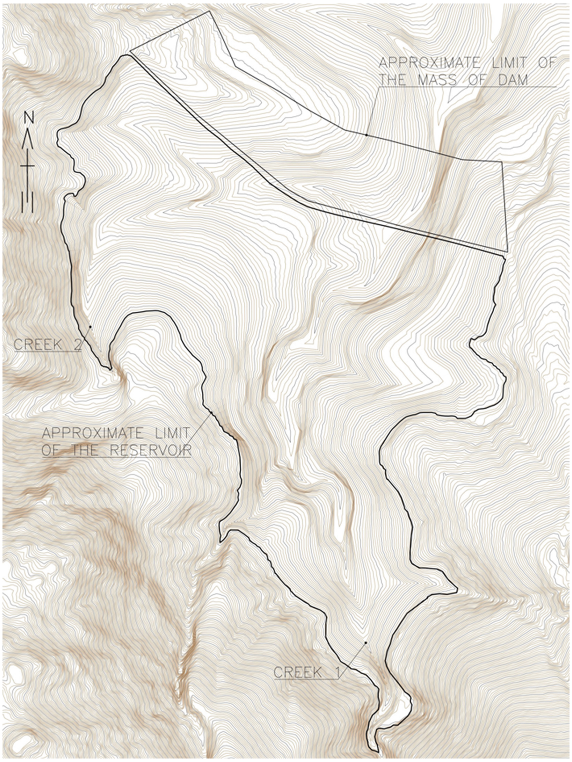

Fig. 3. Original topographic base of the dam area with the approximate boundary of its present reservoir, made using AutoCad software from Autodesk.

The deposition of the tailings in the dam reservoir occurred in a stratified manner, with a decrease in particle size from the bottom to the top, along the stream valley. At the bottom of the valley, the coarser particles were deposited, which make up the type 4 tailings, because in this region the highest energy flows have occurred, as well as in the upstream region of the reservoir, where the tailings were released into the dam. As the flow lost energy, both laterally and vertically, the finer particles that make up the type 3, 2 and 1 tailings were deposited.

The different tailings groups were deposited in a manner similar to the sediment deposition described by the theory of sequence stratigraphy. According to Catuneanu *et al.* (2011), this methodology has as a fundamental criterion the changes in the stacking pattern of sedimentary facies induced by variations in sediment accommodation and supply over time.

It was noted that the upper layer of the reservoir consists of tailings with a predominantly clayey texture and, at the bottom of the reservoir, associated with the talweg regions where the transport of particles occurred in a higher energy regime, the presence of tailings with an essentially sandy texture.

In Fig. 3, which shows the original topography of the dam reservoir, it is possible to verify that this structure covers a portion of the valley characterized by the confluence of two major water courses, which are in turn fed by a series of smaller drainages that configure a dense dendritic drainage pattern in the region under consideration. Most of the type 3 and 4 tailings occupy the lower portion of the basin.

5 Geological-Geotechnical Investigation Campaigns

The dam in question was the scene of numerous investigation campaigns, including boreholes and CPTU tests.

5.1 Boreholes

The boreholes drilled over the reservoir sampled, from top to bottom, alternating layers of tailings showing clayey-silt to sandy-silt textures, reddish brown to dark gray in color, sometimes rich in iron ore fines. Crossing the contact of the tailings with the foundation, the core samples sampled locally silty-clayey to clayey-siltstone residual soil ranging in color from whitish ochre yellow to reddish brown.

5.2 Piezocone Tests - CPTU

The CPTU test allows for the analysis of the geotechnical behavior of fine granular soils of low consistency/compactness. For the target reservoir of the studies, the CPTU tests performed identified the stratifications present in the tailings as expected. It was found that the upper layer of the reservoir consists of tailings with an essentially clayey texture and that the portions at the bottom of the slope are predominantly filled with sandy textured tailings.

6 Geological-Geotechnical Model

From the concatenation of the information obtained from the investigation campaigns, the geological-geotechnical sections show the distribution and thickness of the different types of tailings at depth in the reservoir region. Figures 4, 5 and 6 show the geological-geotechnical model of the dam in plan and sections, as well as the distribution of the different types of tailings in the dam reservoir. The legend of the figures can be found in Fig. 7.

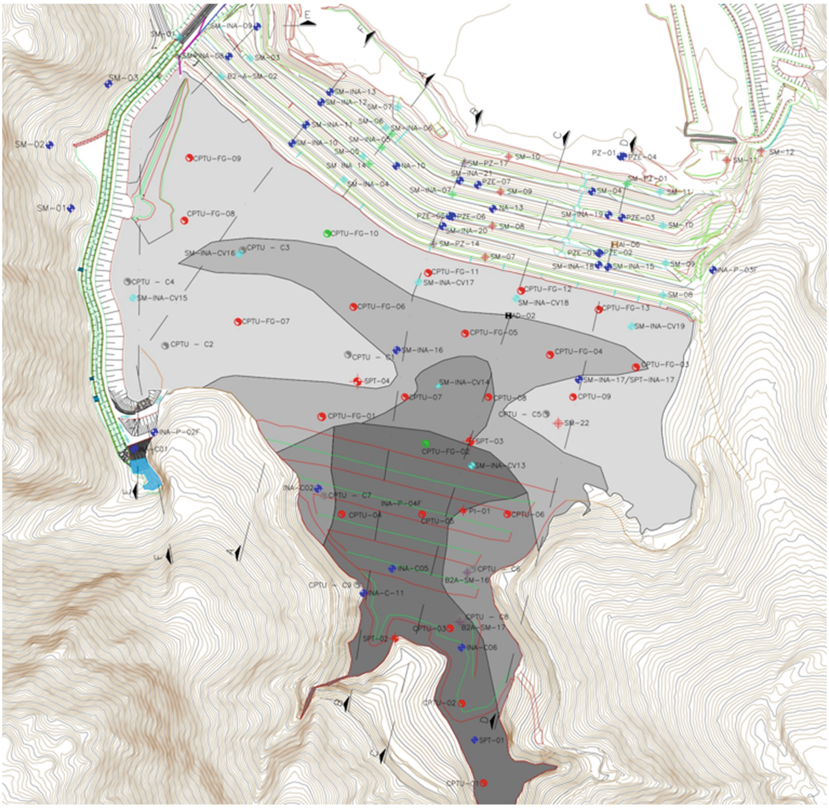

Fig. 4. Map of the dam showing the distribution of tailings in the reservoir, made using AutoCad software from Autodesk.

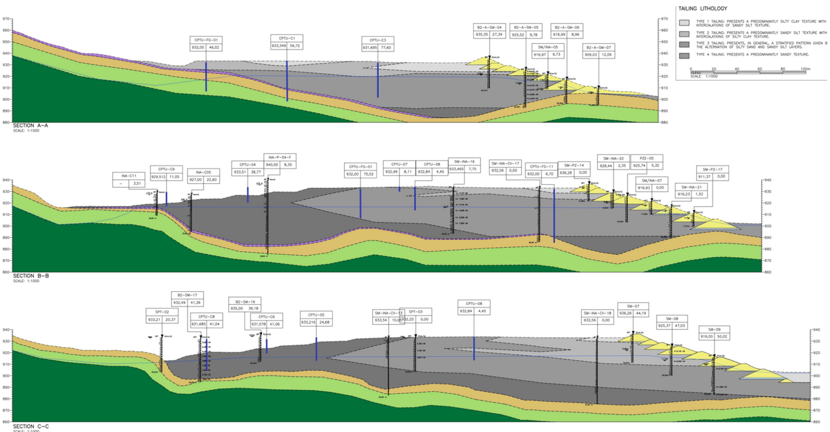

Fig. 5. Geological-geotechnical sections A-A, B-B and C-C showing the distribution of tailings along the dam reservoir, made using AutoCad software from Autodesk.

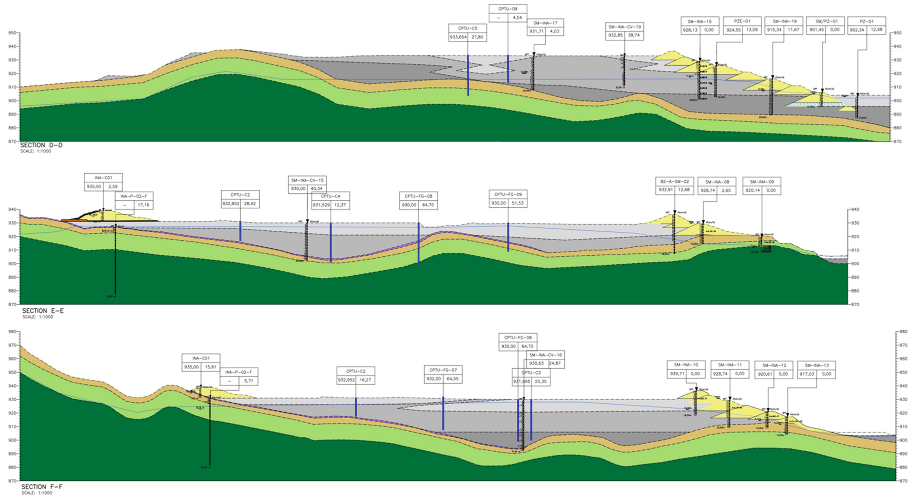

Fig. 6. Geological-geotechnical sections D-D, E-E and F-F showing the distribution of tailings along the dam reservoir, made using AutoCad software from Autodesk.

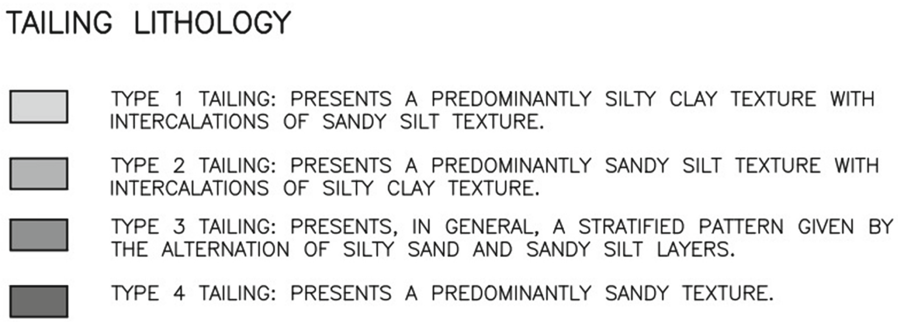

Fig. 7. Legend for the previous geological-geotechnical sections.

7 Geophysical Studies

Data from geophysical surveys through the methodologies of two-dimensional electrical imaging (electroresistivity), with the use of the Schlumberger array, were generated in the region of the reservoir under study. The purpose of these surveys was to map low and high resistivity geophysical anomalies in the reservoir structure, as these anomalies within the body of a dam may indicate areas with greater porosity and a higher degree of saturation.

It can be seen in Fig. 8 that the regions with the lowest resistivities correspond to the portions of saturated tailings (type 2, 3 and 4 tailings), which favor water percolation, confirming the interpretations made through the CPTU test results. It is also observed that in the lower portion of the mass of dam there are zones of low resistivity associated with the portions of the mass of dam where water emergences are observed.

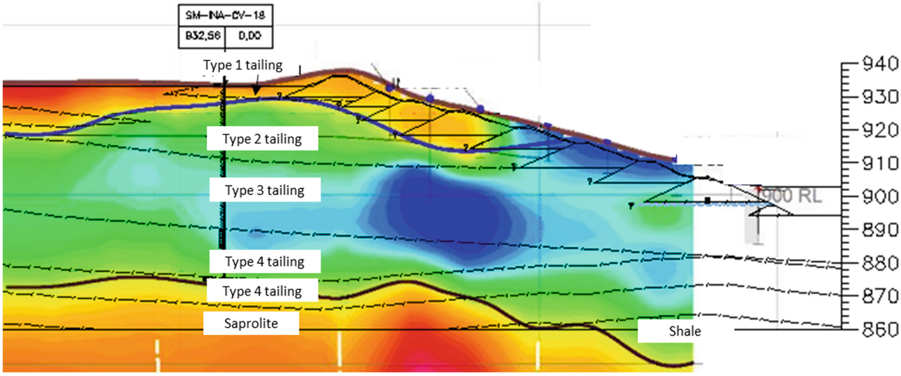

Fig. 8. Geological-geotechnical C-C section confronted with electroresistivity results.

The portions of the tailings located above the water level presented higher resistivities due to the presence of air, which has high impedance, filling the pores left between the grains.

The contact of the tailings with the foundation is given by a transition zone going from low resistivities of about 100 Ω.m to values higher than 600 Ω.m in depth. The lowest values, less than 200 Ω.m (blue), at the foundation, could be explained by the sandy-silt texture, predominant in the residual soil, which when saturated present low resistivities, as well as the sandy tailings. With increasing depth there is a tendency to reduce the void ratio and, consequently, the conductivity.

8 Conclusions

As the results of the geological-geotechnical investigation have shown, the dam reservoir is positioned on a foundation composed of residual shale soil with a silty-clayey texture, covered by a narrow layer of thallus. Underlying the residual soil horizon is the saprolite horizon of the shale, with a sandy-silty to silty texture. Beneath the saprolite is altered to moderately altered, highly fractured shale with very soft to medium strength.

The reservoir is composed of iron ore tailings that present different geotechnical behaviors, as shown by the results of the CPTU tests. For this reason, this unit was divided into four subunits, namely: type 1 tailings of predominantly clayey-siltstone texture with sandy-siltstone intercalations; type 2 tailings of predominantly sandy-siltstone texture with intercalations of clayey-siltstone texture; type 3 tailings of predominantly sandy-siltstone texture with intercalations of sandy-siltstone texture; and type 4 tailings of predominantly sandy texture. This sectoring of the tailings in the reservoir allows the evaluation of the stability of the dam to be more faithful to reality, indicating the region's most susceptible to liquefaction.

The geophysical surveys were performed in order to assist in the identification of the saturated tailings (type 2, 3 and 4 tailings), in which water percolation occurs, and of the tailings-foundation contact. It was thus verified that the proposed tailings-foundation contact of the geological model based on the concatenation of the original topography with the boreholes and CPTU tests is adherent with the geophysical results obtained. At the points where no borehole information is available, the topography was corroborated by geophysics.

It should be noted that for an assertive interpretation a good database is required. No method of obtaining data is systematically conclusive, it becomes evident the various correlations and gains in the definition of a geological model from the junction of invasive and non-invasive methods that will allow the definition of the model corresponding to that found in the field.

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