# Performance and prediction of soft clay behavior under vacuum conditions

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# PERFORMANCE AND PREDICTION OF SOFT CLAY BEHAVIOR UNDER VACUUM CONDITIONS

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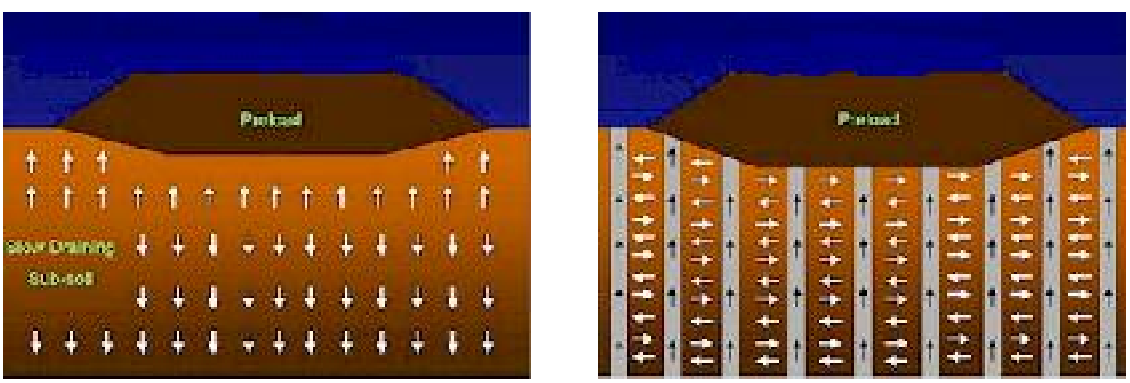
## ABSTRACT

This paper describes the behavior of soft soil foundation under vacuum-assisted preloading at the Second Bangkok International Airport, Thailand. An analytical solution considering the variation of soil permeability and compressibility is proposed. The associated settlement and excess pore pressure at the embankment centerline are predicted and compared with the available field measurement. The field data show that the efficiency of this improvement technique depends on the magnitude and distribution of vacuum pressure as well as on the extent of air leak protection. The height of sand surcharge and consolidation time can be significantly reduced in comparison with the conventional method of surcharge alone.

## 1. INTRODUCTION

Many coastal regions of Australia and Southeast Asia contain very soft clays, which possess poor geotechnical properties such as high compressibility and very low bearing capacity (Indraratna et al., 1992). The construction of highway and railway embankments on normally consolidated soft soil deposits has been affected by the excessive differential settlements, lateral displacements in the absence of an appropriate ground improvement prior to construction. To prevent the unfavorable conditions, the application of preloading with prefbricated vertical drains (PVDs) prior to the construction has been popularly employed in many large scale projects (Hansbo, 1979; QDMR, 1991; Indraratna and Redana, 2000; Chu et al., 2004) . This method accelerates the consolidation by providing a shorter drainge path (Fig. 1). The gained shear strngth of the foundation can be achieved due to rapid excess pore pressure dissipation. It is also well-known that the high outward lateral movement causing the embankment instability can also be reduced via this method.




(a) (b)

**Figure 1** Effect of vertical drain on drainage path; (a) without vertical drains and (b) with PVDs (http://www.americandrainagesystems.com/wick_drains.htm)

In the case of hydraulic fill used in land reclamation projects where the height of surcharge is restricted due to the low shear strength of soft soil, vacuum-assisted consolidation is an ideal method for ground improvement (e.g. reclaimed land) (Shang et al., 1998; Indraratna et al., 2004; Chu and Yan, 2005). The application of vacuum pressure as apparent surchage load with PVDs can be used as a replacement of high embankment fill (Choa, 1990). Vacuum preloading method was first introduced by Kjellman (1952) to improve the strength of soft soil. The applied negative vacuum pressure is propagated along the PVDs length to deep subsoil layer, resulting in an increase in lateral hydraulic gradients ($i = \frac{1}{\gamma_w}\left\{\frac{\partial u}{\partial r} + \frac{\partial u_{vac}}{\partial r}\right\}$) and effective stresses in soil where $u$ and $u_{vac}$ are excess pore pressure generated by preloading and suction pressure generated by vacuum pump, resprectively. Consolidation can be accelerated without increasing excess pore pressure (Cognon et al., 1994; Qain et al., 1992).

In this paper, rigorous analytical solutions for radial consolidation under vacuum condition incorporating non-linear soil properties (e.g. compressibility and permeability) are introduced. Subsequenlty, a case history constructed on soft Bangkok clay is analysed based on the current solution, and compared to field measurements.

## 2. THEORETICAL BACKGROUND FOR VACUUM PRELOADING

### 2.1. VACUUM PRELOADING PRINCIPLES

In saturated soils, the total stress (σ) at any point within the soil mass is the combination of the effective stress (σ') and the pore pressure (u) (Terzaghi, 1943). Thus, the total stress at any point within the soil mass can be written as:

$$\sigma' = \sigma - (+u_{\Delta p}) \tag{1}$$

Under the surcharge load alone, the effective stress is gained by the dissipation of positive excess pore water pressure after the load application. In contrast, the effective stress is increased by the applied negative pore pressure ($-u_{vac}$) under the vacuum condition. Equation (1) can be rewritten based on the vacuum and fill preloading as:

$$\sigma' = \sigma - (+u_{\Delta p}) - (-u_{vac}) \tag{2}$$

It can be seen that the effective stress increases by negative suction, thereby, reducing the risk of shear failure. The performance of this system depends on the vacuum condition under the airtight membrane (Indraratna et al. 2004). The intensive pore pressure measurement under membrane should be performed to verify the reliability of the vacuum system. Figure 2 shows the system of vacuum assisted preloading via PVDs.

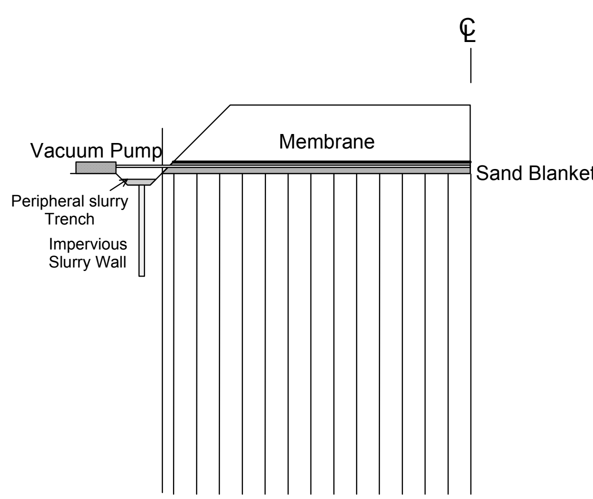



**Figure 2** System of PVDs with sand blanket, airtight membrane and surcharge preloading (Indraratna et al. 2005)

## 2.2. ANALYTICAL SOLUTIONS FOR VACUUM PRELOADING

The unit cell theory is usually employed in the analysis of radial consolidation of soil around a single drain at the location of the embankment centreline where the lateral displacement is negligible (Barron, 1948; Hansbo, 1981). However, the solutions based on the surcharge load condition were simplified using the constant compressibility and permeability. Indraratna et al. (2005) proposed a comprehensive analytical solution for a unit cell under vacuum condition considering the constant soil compressibility and soil permeability. The details of the derivation were explained elsewhere in Indraratna et al., 2005. Figure 3a shows the unit cell and its dimension. Based on the laboratory observation by Indraratna et al. (2004), Figure 3b illustrates the linear variation of vacuum pressure distributed along the drain length interface.

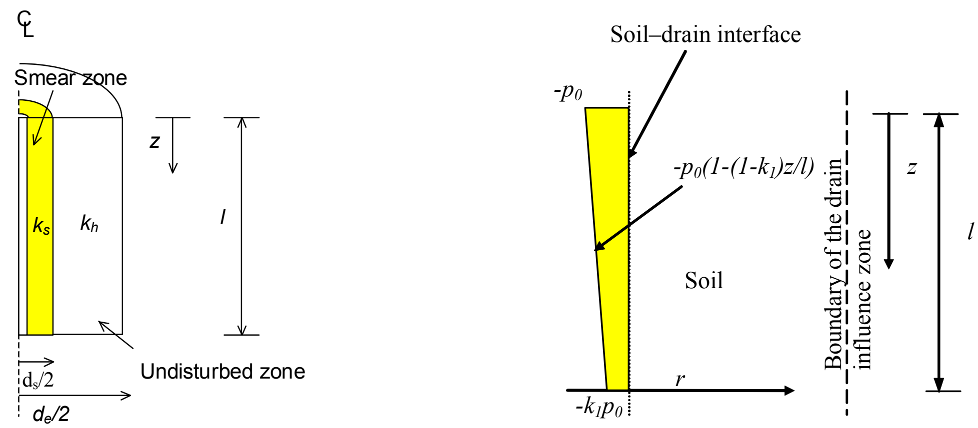



**Figure 3** (a) Unit cell and (b) Vacuum pressure distribution along the drain length

The dissipation rate of average excess pore pressure $\bar{u}_t$ at any time factor ($T_h$) can be expressed as:

$$\bar{u}_t = \left(\Delta p + p_0\frac{(1+k_1)}{2}\right)\exp\left(\frac{-8T_h*}{\mu}\right) - p_0\frac{(1+k_1)}{2} \quad (3)$$

In the above expression,

$$T_h* = P_{av}T_h \quad (4)$$

$$P_{av} = 0.5\left[1 + \left(1 + \Delta p/\sigma'_i + p_0(1+k_1)/2\sigma'_i\right)^{1-C_c/C_k}\right] \quad (5)$$

$$T_h = c_h t / d_e^2 \quad (6)$$

$$\mu = \ln\frac{n}{s} + \frac{k_h}{k'_h}\ln s - 0.75 \quad (7)$$

where, $\mu$ = a group of parameters representing the geometry of the vertical drain system and smear effect, $n = d_e/d_w$, $s = d_s/d_w$, $d_e$ = equivalent diameter of cylinder of soil around drain, $d_s$ = diameter of smear zone and $d_w$ = diameter of drain well, $k_h$ = average horizontal permeability in the undistrubed zone (m/s), $k'_h$ = average horizontal permeability in the smear zone (m/s). $\Delta p$ = preloading pressure, $T_h$ is the dimensionless time factor for consolidation due to radial drainage, $C_c$ = the compressibility indices, $C_c$ = the permeability change index.

The average degree of consolidation ($U_h$) can now be evaluated conveniently by the equation:

$$U_h(\%) = \frac{1-\bar{u}}{1-\bar{u}_\infty} \times 100 \ , \tag{8}$$

where, $\bar{u}_\infty$ can be calculated by Equations 1 and 6 when $t \to \infty$.

The settlement (strain) based on average degree of consolidation is defined by:

$$\rho = \rho_\infty U_h \tag{9}$$

where, $\rho_\infty$ is the ultimate settlement when $t \to \infty$.

# 3. APPLICATION TO A CASE HISTORY

## 3.1. EMBANKMENT DETAILS AND SITE CHARACTERISTICS

The Second Bangkok International Airport is located at Samut Prakan province near the city of Bangkok, Thailand. At this site, soft clays, mainly of marine or estuarine, often have construction difficulties such as excessive differential settlement and foundation failure due to the insufficient of soil shear strength. Therefore, a suitable ground improvement scheme is required prior to the infrastructure construction. Due to the scarcity of good fill material and time limitation, the vacuum preloading combined with a very low height of surcharge fill via PVDs was selected to improve soft soil shear strength in this project.

Figure 4 shows the shear strength and compressibility ratio of sub-soil layers. The minimum undrained shear strength ($C_u$) of topmost weathered clay is about 18 kPa at a depth of 1 m. This value decreases to 8-15 kPa in the very soft underlying clay layer, which is highly compressible. The weathered crust is much less compressible due to its desiccation and compaction. The compression ratio of the soft clay layer varies from 0.3-0.5, whereas the weathered crust has a compressibility ratio of about 0.2. The soil layer at the crust is highly overconsolidated (OCR ~ 2.4-26) due to aging, desiccation and oxidation process.

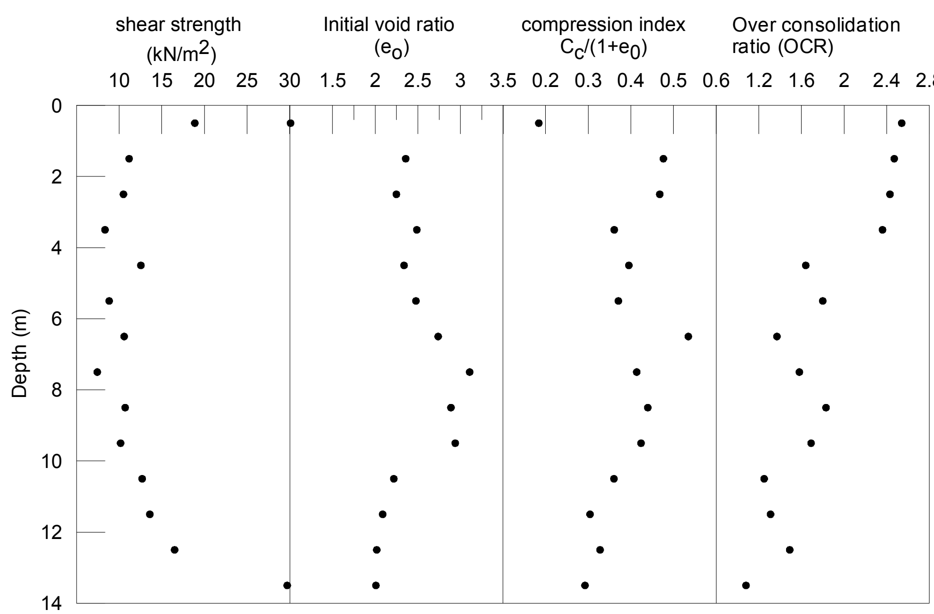



**Figure 4** Average strength and compressibility indices (After Sangmala, 1997)

At this site, Embankment TV2 was raised with 12 m PVDs@1.0m drain spacing and -70 kPa vacuum application (Fig. 5). Total base area of each embankment was 40 × 40 $m^2$ (Asian Institute of Technology, 1995). Perforated and corrugated pipes wrapped together in non-woven geotextile were placed under membrane liner. The collection of instrumentation includes piezometers, surface settlement plates, multipoint extensometers, inclinometers, observation wells and benchmarks. The settlement, excess pore water pressure and lateral movement were measured for about 150 days. Figure 6 shows the fill loading history of the embankment.

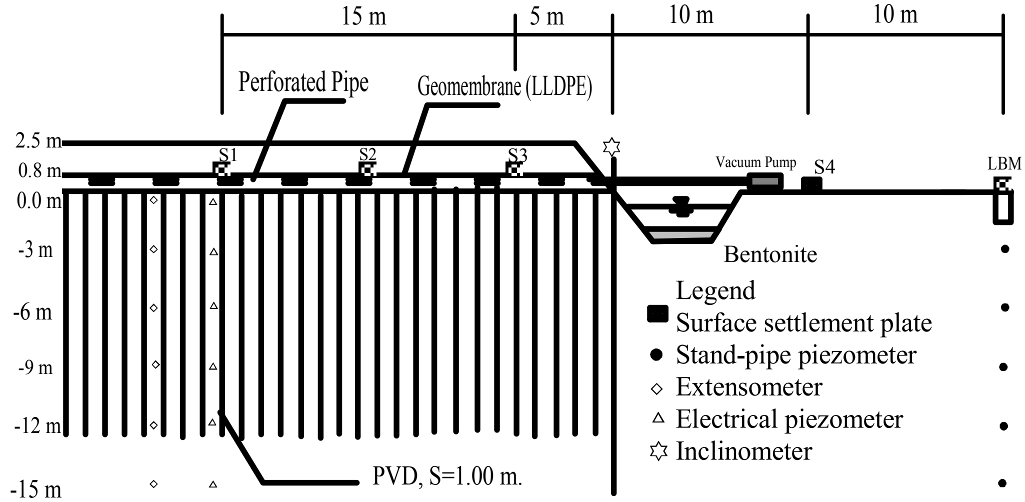



**Figure 5** Cross section and location of monitoring system (after Indraratna and Rujikiatkamjorn, 2004).

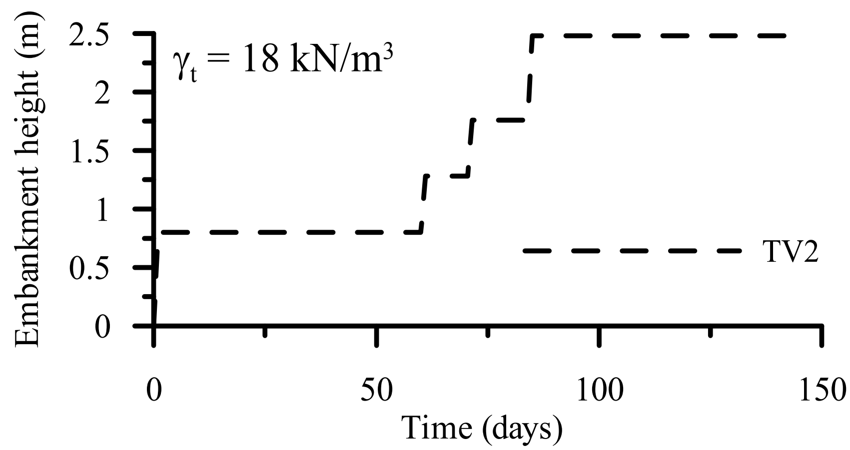



**Figure 6** Construction schedule (after Indraratna and Rujikiatkamjorn, 2004).

### 3.2. SINGLE DRAIN ANALYSIS USING PROPOSED ANALYTICAL MODEL

In the field, at the embankment centerline, the condition of 1-D consolidation assumed in the proposed analytical model can be justified. The soil parameters, the in-situ effective stress and the soil permeability for soft Bangkok clay subsoils are shown in Table 1. The relevant soil properties were obtained from $CK_oU$ triaxial tests (AIT, 1995). The slope of e-log$k_h$ ($C_k$) can be determined by (Tavenas et al., 1983, Indraratna et al. 2005):

$$C_k = 0.5e_0 \tag{10}$$

In the analysis, each subsoil layer was divided into 12 sub-layers (approximately 1m thick) to obtain a more accurate effective stress distribution with depth. The value of soil compressibility indices ($C_c$ or $C_r$) are related to the actual stress state, where the current effective stress must be considered in association with the pre-consolidation pressure of soil at that particular depth (Indraratna et al., 1994). The values of $k_h/k_s$ and $d_s/d_w$ for this case study were assumed to be 2 and 6, respectively.
The embankment loading was simulated using an instantaneous loading at the upper boundary. Settlement predictions were carried out at the embankment centerline using Equations (3)-(10). At the beginning of the subsequent stage, the initial in-situ effective stress and soil permeability were calculated based on the final degree of consolidation of the previous loading stage. As the computation of consolidation settlement at the centerline is uncomplicated and follows the 1-D consolidation theory, the use of an EXCEL spreadsheet formulation for this purpose is sufficient. For the first stage loading, where the effective pre-consolidation pressure ($p'_c$) is not exceeded, the value of recompression index ($C_r$) may be used. In particular, the surface crust is heavily over-consolidated (up to about 2 m depth). Once $p'_c$ is exceeded, the value of compression index ($C_c$) follows the normally consolidated line as indicated by the values in Table 1.

The following 4 models were analysed:

- Model A: Application of surcharge load alone (i.e., no vacuum application),
- Model B: Application of surcharge and time dependent vacuum pressure simulating vacuum loss according to the measured vacuum pressure under membrane (Fig. 7). However, the soil compressibility and permability is assumed to be constant (Hansbo, 1981)
- Model C: Similar to Model B. The nonlinear variation of soil compressibility and permeability proposed by the Authors is employed
- Model D: Similar to Model C. There is no vacuum loss after 1 month

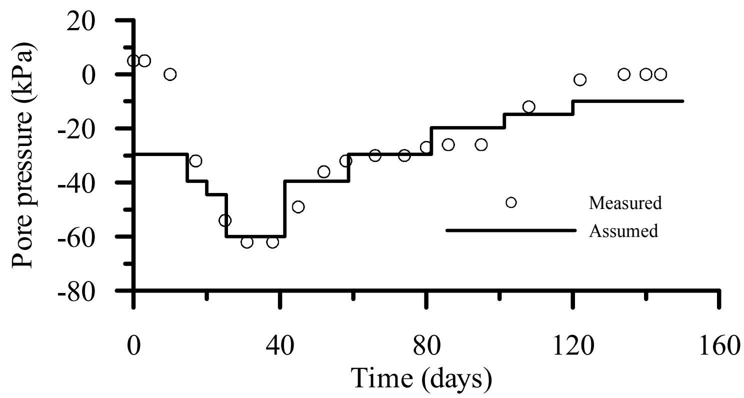



**Figure 7** Measured and assumed pore pressure

**Table 1** Selected soil parameters for single drain analysis

| Depth (m) | $C_r$ | $C_c$ | $k_h$ ($\times 10^{-9}$ m/s) | $e_0$ | $\gamma$ (kN/m$^3$) | $p'_c$ (kPa) |
|---|---|---|---|---|---|---|
| 0.0-2.0 | 0.06 | 0.37 | 30.1 | 1.8 | 16 | 58 |
| 2.0-8.5 | 0.08 | 1.6 | 12.7 | 2.8 | 15 | 45 |
| 8.5-10.5 | 0.05 | 1.7 | 6.02 | 2.4 | 15 | 70 |
| 10.5-13.0 | 0.03 | 0.95 | 2.56 | 1.8 | 16 | 80 |
| 13.0-15.0 | 0.01 | 0.88 | 0.60 | 1.2 | 18 | 90 |

Figure 8 compares the predicted surface centreline settlement with the measured data. As expected, the predicted results based on the proposed solutions agree well with the measured results, whereas the prediction based on the constant $k_h$ overestimates settlement after 80 days, because, the actual soil permeability decreases considerably at higher stress levels. It was verified that the combined vacuum application and the PVDs system accelerates consolidation, while the vacuum pressure performs as an additional surcharge load. As shown in Figure 8, 'no leakage' condition gains more settlements, whereas the prediction without any vacuum application yields less settlement. The efficiency depends entirely on preventing airleaks and the distribution of vacuum pressure along the length of the drain. It is noted that the ultimate settlement can be obtained after 170 days.

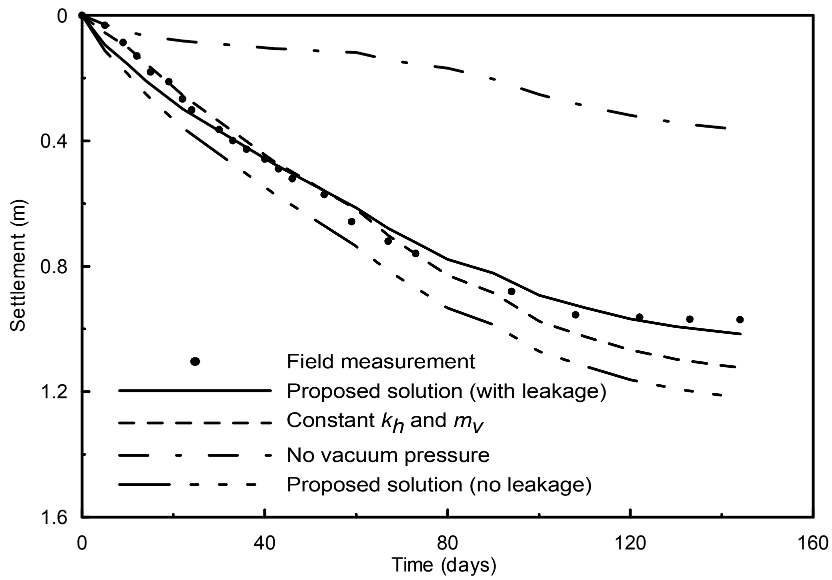



**Figure 8** Surface settlement predictions at the centerline

# 4. CONCLUSIONS

A system of prefabricated vertical drains (PVDs) combined with vacuum preloading is an effective method for accelerating soil consolidation. In this study, a revised analytical model for vacuum preloading incorporating the compressibility indices ($C_c$ and $C_r$) was proposed, and the variation of horizontal permeability coefficient ($k_h$) was represented by the $e$-log$k_h$ relationship. The solution was employed to evaluate the performance of soft clay beneath embankment TV2 using spreadsheet software. The settlement predictions of the soft clay foundation were agreed well with field observations when considering the actual field condition such as the varations of vacuum pressure, soil compressibility and permeabiltiy. It showed that the assumption of vacuum pressure distribution along the drain length could be applied to this site as evidenced by the monitored data. The effectiveness of vacuum system depends on the air leak protection in the field.

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