Modelling numerically the life-cycle of coal mine tailings

Un modèle numérique de la vie utile de rejets de mines de charbon soumis à des chargements cycliques

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SYNOPSIS: The processing of run-of-mine coal produces a fine grained (predominantly silt and clay sized) waste which is conventionally pumped as a thickened slurry to be deposited in tailings dams or ponds. On deposition, the tailings undergo sedimentation, consolidation and eventually crusting or desiccation. The paper concentrates on the processes of consolidation and crusting. The life-cycle and results of field monitoring of coal mine tailings at a particular mine are presented, and using the results of laboratory testing to provide input data, the observed behaviour is modelled numerically.

1 INTRODUCTION

The disposal of coal mine tailings is a non-productive exercise and the techniques employed are aimed at minimising the cost of disposal. As a result, there has been an emphasis on the containment of tailings slurry with little consideration given to dewatering or to the eventual rehabilitation of the disposal area. Only at mines where water or available disposal areas are in short supply, are attempts made to mechanically dewater the tailings slurry within the processing plant. However, growing environmental, legislative and economic pressures are forcing consideration be given to optimising disposal techniques and to rehabilitation of dis-used tailings disposal areas. Before significant progress can be made towards optimising coal mine tailings disposal, dewatering and rehabilitation, the behaviour of the tailings deposited as a slurry must be understood and means of predicting the behaviour found. This paper goes some way towards meeting these needs.

2 CHARACTERISATION OF THE COAL MINE TAILINGS

Field and laboratory studies have been conducted on coal mine tailings from New Hope Colliery in the Bundamba District of the West Moreton Coalfields, near Ipswich in South-Eastern Queensland, Australia. The New Hope tailings contain 20 to 40% clay size, 30 to 50% silt size and 30% or less fine sand size particles. The liquid limit of the material is in the range 38 to 58% and the plasticity index is in the range 13 to 30%. The material falls largely within the low plasticity clay range just above the Casagrande A-line. In their specific gravity, coal mine tailings depart significantly from normal soils. The substantial coal content of coal mine tailings lowers the average specific gravity of the material. The specific gravity of New Hope tailings is in the range 1.67 to 1.85, with a mean value of 1.76. The range for the fraction passing the 75µm sieve is 1.76 to 1.92, with a mean value of 1.84. Norman (1960) published mean specific gravities for coal of 1.28 and for mineral matter of 2.68 for the Bundamba District. Using these values, the estimated mean coal content of the all-in New Hope tailings and of the -75µm fraction are 66% and 60%, respectively.

3 LIFE-CYCLE OF NEW HOPE TAILINGS

In the processing of New Hope coal, flocculants are added to the finer fractions to promote sedimention and thickening, resulting in a tailings slurry with a solids concentration of about 30% by weight. This corresponds to an overall moisture content relative to the weight of solids of 233% and a mean void ratio of 4.1 (assuming that the slurry is fully water saturated). However, the tailings ponds at New Hope Colliery are located about 2 km from the washery where the tailings are produced. To accommodate this long pumping distance, the tailings must first be watered down to about 15% solids by weight (a moisture content of 567% and mean void ratio of 10.0).

On deposition at 15% solids by weight, the tailings slurry undergoes considerable sedimentation to form relatively quickly a sediment with a solids concentration of about 46%, a moisture content of about 119% and a mean void ratio of about 2.0. These values are based on the results of laboratory sedimentation tests. As hindered sedimentation continues at a slow rate, the tailings sediment begins to take on soil-like behaviour. Eventually excess pores pressures are generated by the self-weight of the sediment and, as these dissipate, consolidation and the build-up of effective stress take place. Consolidation continues at a decreasing rate as the driving hydraulic gradients diminish and as the permeability of the consolidating sediment reduces. The dissipation of excess pore pressures will be fastest adjacent to drainage boundaries, where it will be accompanied by rapid consolidation and a rapid drop-off in permeability. The permeability gradient towards a drainage boundary inhibits the drainage of the less consolidated and more permeable regions more distant from the drainage boundary.

At New Hope Colliery, much of the deposited tailings slurry remains covered by water as it consolidates and further slurry builds up. The low self-weight stresses involved mean that the sediment remains very soft even after consolidation of a particular layer becomes essentially complete. When the storage is full, the ponded surface water is removed by pumping, evaporation or breaching of the containment embankment and the surface becomes exposed to drying. Pore water suctions are generated which cause the sediment to shrink and increase in strength towards the surface. As crusting proceeds the watertable drops below the surface, but the process is at least partially reversible on rewetting. The sediment remains normally consolidated during consolidation under water and initial crusting, but subsequent rewetting and cycles of wetting and drying cause oversonsolidation.

4 FIELD STUDIES AT NEW HOPE COLLIERY

4.1 Vane shear testing

In situ vane shear testing was carried out in tailings Pit 21 at New Hope Colliery using a 55 mm diameter by 110 mm long vane operated by hand with a calibrated torque wrench. The testing was done in crusted tailings about 2.18 m deep in four hand auger holes in close proximity. The tailings had been allowed to crust for about 28.5 months following abandonment of the tailings pit and were probably near their driest ever state at the time of testing (that is, normally consolidated to lightly overconsolidated). Prior to each vane test, the hand auger was advanced to about 50 mm above the desired test interval, the vane was inserted and, after a brief interval (about 20 s) to allow dissipation of any pore pressures generated on insertion, rotated to obtain the peak vane shear strength. The average rate of rotation used was about $7.5^o.s^{-1}$. Using the arguments presented by Blight(1968) relating to field vane testing of silty soils, it can be shown that this rate of rotation allows less than 5% dissipation of rotation-induced pore pressures and therefore provides a good estimate of the undrained shear strength of the tailings.

The measured undrained shear strengths s_u are plotted against depth on Figure 1. The scatter of results is due in part to the variation of the tailings with depth and area. Towards the surface, cycles of wetting and drying (leading to overconsolidation) are most likely responsible for the more marked scatter. To facilitate later comparisons with numerical estimates of the undrained shear strength profile with depth, a line of best fit has been drawn through the data on Figure 1.

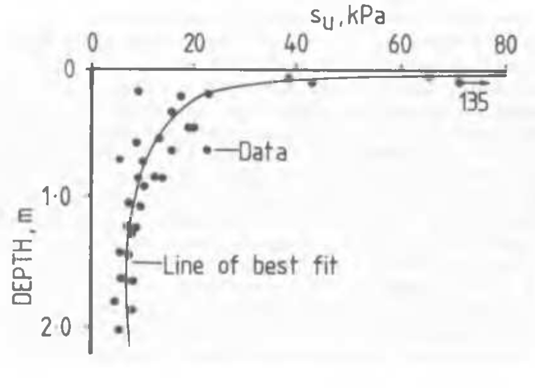

Figure 1. Undrained shear strength s_u versus depth.

4.2 Moisture content and suction determinations

Following each vane test, a bag sample of the tailings from the test interval was recovered. For samples below 0.3 m depth, the laboratory determined moisture content of the tailings increased gradually from about 38% at 0.3 m depth to a constant value of about 50% from 1.4 m depth, the location of the watertable. As these moisture contents fall within the range of liquid limit measured for the tailings, it is likely that the tailings was fully saturated below 0.3 m depth. The moisture content of samples from above 0.3 m depth decreases towards the surface. At 0.2 m depth it is about 18%, approximately the plastic limit of the tailings which marks the onset of significant desaturation. Filter paper based measurement of the matrix and total suctions of New Hope tailings over the moisture content range 32 to 18%, during drying, indicated total suctions in the range 200 to 1200 kPa.

4.3 Monitoring of settlement during crusting

In another part of Pit 21 at New Hope Colliery, adjacent to ponded water on the surface of the tailings, monitoring of the settlement of the tailings druing crusting has been carried out over a 16 month period. Within this time, the surface of the tailings has settled a net 120 mm. Levels have been taken at monthly intervals and show the rate of settlement to be strongly dependent on the occurrence of rainfall, particularly if rainfall leads to the ponding of runoff on the surface of the tailings. Prolonged heavy rainfall leading to prolonged ponding can cause a reversal of the crusting process with the surface rising above its previous level. The maximum amount of surface settlement in any one month was 17 mm, with an average settlement rate over the 16 month monitoring period of $7.5\ mm.month^{-1}$. Using this average rate, the crusting settlement in the vicinity of the vane shear testing would have been of the order of 200 mm over the 28.5 months available for crusting.

5 NUMERICAL ANALYSIS

The aim of the analysis was to model numerically the consolidation and crusting processes as experienced by New Hope Colliery tailings. This was achieved using the computer program TAIL (Carter and Williams, 1988).

5.1 Description of computer program

The program TAIL analyses one-dimensional consolidation of a soil by the finite element method. The soil is assumed to be saturated and the mechanical behaviour of the skeleton is represented by the Modified Cam-clay soil model. The flow of pore fluid through the soil is governed by Darcy's law, with a variable coefficient of permeability depending on the current void ratio. Finite (large) strain analysis is incorporated in the program and self-weight consolidation and crusting are among the 'loading' options available. Self-weight consolidation is modelled by adding soil, one layer at a time, to the top of the current layer. Crusting is modelled by applying increments of negative pore pressure (suction) at the top of the deposit and marching time on to cause a lowering of the watertable, with accompanying settlement and stiffening towards the top of the deposit. Both normally consolidated and overconsolidated conditions may be modelled.

The Modified Cam-clay soil model has been described elsewhere (Britto and Gunn,1987, for example) and will not be detailed herein. For the ideal material, it is assumed that the critical state condition occurs whenever

$$q = Mp' \qquad (1)$$

and

$$e = e_{cs} - \lambda \ln(p') \qquad (2)$$

where q and p' are the deviatoric and mean effective stresses, respectively,

M is the slope of the critical state line in p'-q space,

e is the void ratio of the soil,

e_{cs} is the critical state void ratio at $p' = 1kPa$, a material constant, and

λ is the slope of the normal consolidation line under isotropic effective stress conditions in e -ln(p') space, a material constant.

For effective stress states inside the elliptical yield surface, the behaviour is elastic and the elastic bulk modulus K and shear modulus G are assumed to vary as follows

$$K = \frac{(1 + e)p'}{\kappa}, \text{ and} \qquad (3)$$

$$G = G_a + G_b p_c' \qquad (4)$$

where κ is the slope of the unloading-reloading lines in e - ln(p') space, a material constant,

G_a and G_b are considered to be material constants, with G_b allowing G to vary with the current size of the elliptical yield surface, defined by p_c'.

Drainage may occur in either vertical direction. The coefficient of vertical permeability k_v is dependent on e as follows

$$k_v = a(e - e_m)^b, \text{ for e} \quad e>e_m \qquad (5a)$$

$$k_v = 0^+ \quad , \text{ for e} \quad e<e_m \qquad (5b)$$

where a, b and e_m are considered to be material constants.

Equation (5a) reflects the power law relation between k_v and e found empirically for other soils by, for example, Al-Tabbaa and Wood (1986). The inclusion of the limiting void ratio e_m accounts for the lightly cemented cardhouse structure which sedimented coal tailings appear to assume on crusting.

5.2 Selection of material constants

Limited laboratory testing of New Hope tailings was carried out to assist in the selection of material constants for input to the analyses. The laboratory testing of coal tailings is made extremely difficult by its soft and loosely packed nature. Undisturbed sampling cannot be achieved in the very soft uncrusted tailings below the watertable, and crusted tailings are not emenable to thin walled tube sampling as their loosely packed nature cannot be preserved. Block samples of crusted tailings are therefore required. A further problem is that crusted tailings will not be fully saturated and will exist under high suction.

Values for κ and λ obtained from oedometer testing of both crusted and reconstituted tailings samples, were reasonably constant at 0.0036 and 0.0808, respectively. A value for M of 1.0 was assumed. A unique value for e_{cs} could not be obtained since the pore water suction and hence absolute value of p' varied between samples and during oedometer testing, where its measurement was not possible. It was therefore decided to determine the e_{cs} value analytically by fitting the observed behaviour. Sensitivity analyses indicated that the numercial result was not particularly sensitive to the values of G_a and G_b, provided that where only one of the two was used, its value was not too small ($G_a >$ 0.1 kPa or $G_b >$ 10 when p_c' is measured in kPa). It was decided that G would best be defined as a function of p_c' measured in kPa and values for G_a and G_b of 0 and 100 kPa, respectively, were assumed.

Values for a, b and e_m were obtained by fitting a curve of the form given by equation (5a) to k_v - e data calculated from oedometer testing of crusted tailings. This gave values of 2.57 x 10^{-4}m.s^{-1}, 7.48 and 0.4 for a, b and e_m, respectively. Variation of these values showed the numerical result to be not particularly sensitive to the combination of a, b and e_m used to fit the empirical data.

5.3 Numerical modelling of crusting

Since the tailings tested at New Hope Colliery were crusted, most information was known of the state of the tailings following crusting. It was therefore appropriate to model the crusting process first in an attempt to reproduce the undrained shear strength profile with depth for the crusted tailings given on Figure 1. The tailings were considered to be near their driest ever state and were therefore normally consolidated or lightly overconsolidated. These two cases were considered separately.

Case (i) Normally consolidated crusting

Normally consolidated crusting is modelled numerically by the monotonic imposition of pore water suction to the top surface. It was necessary to define an appropriate total amount of suction to apply to represent field conditions, bearing in mind that the numerical model could not allow for the significant desaturation towards the surface and the very high suctions (in excess of 1000 kPa) this would generate. The fit of the numerical result to the observed data might be expected to be poorest towards the desaturated surface. In Williams (1988), critical state theory was used to give a value of 0.24 for the ratio s_u/σ_v' under normally consolidated conditions. From Figure 1, a representative value for s_u at the surface is about 70 kPa, indicating a value of about 300 kPa for σ_v' and hence the pore water suction, since the self-weight stresses are zero at the surface. This level of suction is of an order similar to measured values.

In the absence of detailed knowledge of the progress of crusting, a suction of 300 kPa was applied in 225 increment having a duration of 3.33 x 10^5s to give a total crusting time of 28.5 months. The initial depth of uncrusted tailings and the value of e_{cs} were varied in the analysis to achieve a crusted thickness of close to 2.18 m and a watertable depth of close to 1.4 m. A 26-element mesh, with elements diminishing in thickness towards the surface and upward only drainage were adopted. An initial depth of 2.385 m and a fitted e_{cs} of 0.889 produced a crusted thickness of 2.183 m and a watertable depth of 1.407 m. The settlement of 202 mm during crusting compares extremely well with the earlier estimate of about 200 mm. The computed final profiles of undrained shear strength, vertical effective stress and pore water pressure u are shown on Figures 2, 3 and 4, respectively.
Also shown on Figure 2 is the line of best fit through the observed data taken from Figure 1. Comparing the numerical and observed results shown on Figure 2, the agreement is remarkably good, even close to the surface.

To test the sensitivity of the numerical result to the level of suction to be applied, suctions of 200 kPa and 400 kPa were tested over the total crusting time of 28.5 months using an initial depth of 2.385 m and fitted e_{cs} value of 0.889. Final thicknesses of 2.183 m and 2.185 m and watertable depths of 1.394 m and 1.411 m were obtained for 200 kPa and 400 kPa suction, respectively. The difference in the s_u, σ_v' and u profiles for the three levels of suction were imperceptible below 0.2 m depth and above 0.2 m depth they were only minor. This is due to the very low permeability towards the surface for suctions in the range 200 to 400 kPa.

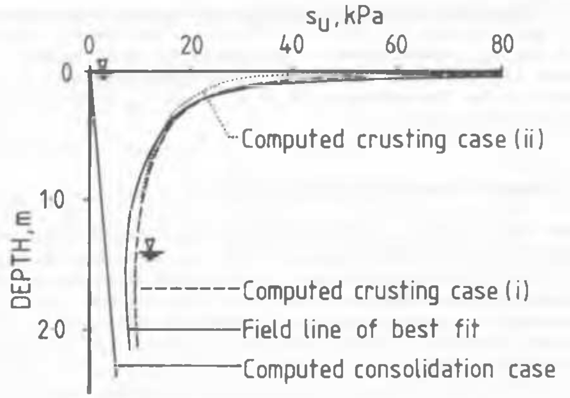

Figure 2. Computed profiles of undrained shear strength s_u with depth.

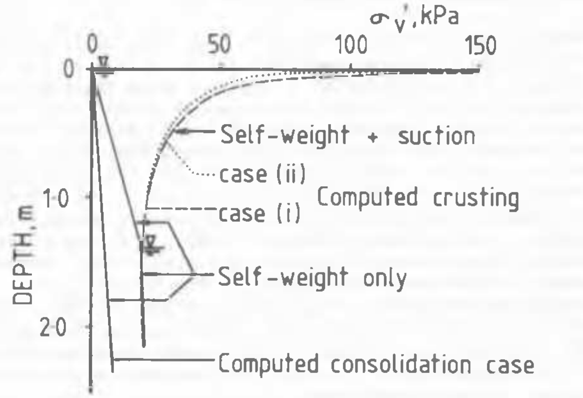

Figure 3. Computed profiles of vertical effective stress σ_v' with depth.

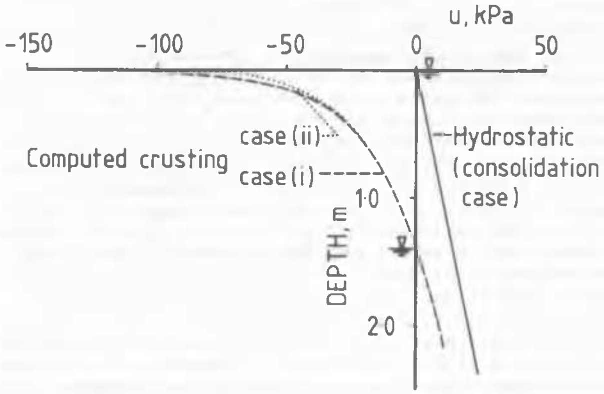

Figure 4. Computed profiles of pore water pressure u with depth.

Case (ii) Lightly overconsolidated crusting

Williams and Morris (1987) estimated the average overconsolidation ratio OCR of the tailings deposit in question to be about 1.7. This estimate was based on excess pore pressures measured within the tailings as the surface was loaded by a trial embankment, using the method outlined by Leroueil et al (1978). On this basis that the tailings were probably near their driest ever state at the time of testing, with the watertable near its lowest ever level, the tailings would have been close to normally consolidated below the watertable. Above the watertable where the tailings would have been subjected to cycles of wetting and drying, the OCR would be expected to rise exponentially towards the surface where a value of about 5 was adopted for the purposes of this analysis. The assumed distribution of OCR with depth is shown on Figure 5. It provides an average OCR over the entire depth of 1.7.

For overconsolidated soils, the ratio $(s_u/\sigma_v')_{oc}$ may be related to the normally consolidated ratio $(s_u/\sigma_v')_{nc}$ of the expression

$$(s_u/\sigma_v')_{oc} = (s_u/\sigma_v')_{nc}\,(OCR)^m \qquad (6)$$

where m is an exponent dependent on soil type and OCR.

Wroth (1984) reported empirical values for m in the range 0.68 to 0.87, with theoretical values typically of 0.8. A value of 0.8 is adopted here, giving a value of 0.36 for $(s_u/\sigma_v')_{oc}$. In the analysis, a value for the at rest coefficient of lateral earth pressure K_0 is also required. For overconsolidated soils, this may be related to the normally consolidated value K_{nc} by the expression

$$K_0 = K_{nc}(OCR)^n \sim (1-\sin\phi')\,(OCR)^n \qquad (7)$$

where n is an exponent dependent on soil type and OCR, and

ϕ' is the effective angle of internal friction of the soil.

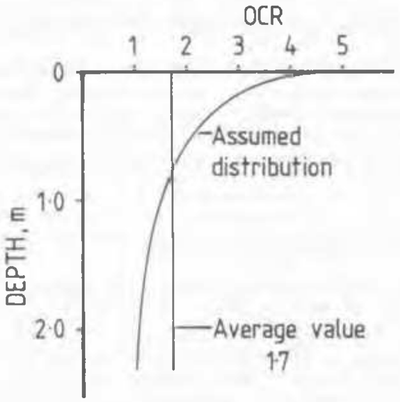

Figure 5. Assumed distribution of overconsolidation ratio OCR with depth for crusting case (ii).

For the purposes of this analysis, a value for n of 0.7 is adopted and the value for ϕ' was based on direct shear testing of crusted coal tailings. In the analysis, the previously fitted value for e_{cs} of 0.889 was adopted, suction was applied in 3.33×10^5s duration increments of 1.33 kPa and the initial thickness of tailings was varied to match the observed crusted thickness and watertable depth. An initial thickness of 2.330 m and a suction of 288 kPa applied over 27.4 months produced a final thickness of 2.183 m and a watertable depth of 1.399 m. The 1.1 months short of the actual 28.5 months may be thought of as the duration of the wetting and drying cycles to produce the assumed lightly overconsolidated state. During light overconsolidation, a settlement of about 55 mm would have taken place. The computed final profiles for case (ii) are shown on Figures 2, 3 and 4.
A comparison between the profiles for cases (i) and (ii) reveals that initial light overconsolidation has little effect on the crusting process. It results in a slight decrease in s_u, σ_v' and suction over the upper third of the profile, which arguably matches field behaviour

slightly better than the normally consolidated case.

5.4 Numerical modelling of consolidation

It is difficult to monitor consolidation in the field and little data has been collected on the process. What is known is that consolidation commences at a void ratio somewhat less than 2.0 and that for consistency, conditions at the end of the consolidation process should be similar to conditions at the start of the crusting process. Since the rate of tailings slurry deposition is unknown, the consolidation process was modelled by the addition of a single layer. Adopting the previously fitted value for e_{cs} of 0.889, the initial thickness of this layer was varied to find the thickness producing a consolidated depth of about 2.385 m, matching the starting thickness in crusting case (i). An initial thickness of 3.135 m produced a consolidated thickness of 2.384 m (751 mm settlement and consolidation largely complete) and the final profiles shown on Figures 2, 3 and 4. These final profiles are in close agreement with the initial profiles set up in the modelling of crusting.

6 DISCUSSION OF RESULTS

The result of the field monitoring and numerical modelling of the processes of consolidation and crusting of slurried New Hope Colliery tailings are summarised in Table 1.

Table 1. Summary of results.

(a) Consolidation

Numerical	Initial thickness (m)	Final thickness (m)	Settlement (mm)
	3.135	2.384	751

(b) Crusting

Field	Final thickness (m)	Settlement (mm)	Watertable depth (m)
	2.18	~200	1.4

Numerical	Av. OCR	Suction (kPa)	Initial thickness (m)	Final thickness (m)	Settlement (mm)	Watertable depth (m)
Case (i)	1.0	300	2.385	2.183	202	1.407
	1.0	200	2.385	2.183	202	1.394
	1.0	400	2.385	2.185	200	1.411
Case (ii)	1.7	288	2.330	2.183	147	1.399

The results presented in Figures 2, 3 and 4 and in Table 1 demonstrate how useful numerical modelling can be in following the consolidation and crusting processes in the life-cycle of coal mine tailings deposited as a slurry. It is seen that the modelling of crusting is not very sensitive to the level of suction applied to the tailings surface or to the initial degree of overconsolidation of the tailings deposit. The key factors are the fitting of observed behaviour to establish the value for e_{cs}, which cannot be determined in the laboratory for soils under unknown pore water suctions, and the time over which the suction is applied to the surface. If sufficient time is allowed the suction will become uniform with depth and equal to the value applied at the surface. In practice sufficient time for this to occur will not be available. The crusting process will be interrrupted, even reversed, by periods of rainfall. In the numerical modelling of crusting, no interruptions were allowed for since details of them are unknown. In practice, very rapid development and loss of suction will occur and some degree of overconsolidation is inevitable as the tailings go through numerous wetting and drying cycles.

The numerical modelling of consolidation is also oversimplified compared with the fields situation. However, for both consolidation and crusting, the end points are often of prime importance and the results presented suggest that these can be defined with reasonable precision despite the oversimplifications made. If the detailed path followed by a tailings deposit were known, it may be possible to reproduce it numerically.

7 CONCLUSIONS

The life-cycle of a typical coal mine tailings deposit has been described, concentrating on the main features of consolidation and crusting. A computer program has been described which allows numerical modelling of the consolidation and crusting processes. The program TAIL has been applied to a particular coal tailings deposit at New Hope Colliery for which field monitoring and laboratory data has been collected. The laboratory data assisted in the selection of material properties for input to the computer program. Other properties were obtained by matching observed behaviour, and the numerical results obtained were consistent within themselves and in remarkably good agreement with field results. The numerical results appear to be not very sensitive to the path through which the tailings are taken between two states. This gives some confidence in the more general application of the program to situations where less data is available.

ACKNOWLEDGEMENTS

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