# THREE-DIMENSIONAL SEEPAGE ANALYSIS THROUGH FORDYCE DAM

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**Abstract:** A three-dimensional model was developed for analyzing the seepage through Fordyce Dam. A two-dimensional analysis of seepage through the dam under-predicts seepage fluxes by a factor of 5 when established hydraulic conductivity values are used for the rock materials. The three-dimensional model provides similar seepage fluxes to the two-dimensional model, when identical conditions are compared. The three-dimensional model was used to explore various alternatives that could be the cause of the observed seepage fluxes, followed by analyses that can guide field monitoring activities to reduce the uncertainty between these alternatives.

## INTRODUCTION

Fordyce Dam, located in the Sierra Nevada Mountains, stores approximately 49,900 acre-feet of water when full. Originally built in 1873 and then raised over time with numerous modifications and additions, the dam is about 1,000 feet long and 135 feet high and consists of an earthen embankment with older placed and dumped rock, newer loose rockfill, an upstream concrete face, and a concrete cutoff wall within the earthen embankment overlying the middle 300 ft of the dam including the former Fordyce Creek Channel, to reduce seepage. Figure 1 schematically depicts the layout and sectional configuration of Fordyce Dam. PG&E (2002) provide details on the construction and setting of the Fordyce Dam and its past and current structural condition. In 1995-1996 extensive repairs were made to the upstream concrete face and slab joints. These repairs reduced the measured leakage from 60 cfs to approximately 25 cfs. Based on several engineering investigations and analyses (PG&E, 1997, 2000; Geomatrix, 2001, 2002; URS, 2003), the Federal Energy Regulatory Commission (FERC) has concluded that a seepage monitoring program needs to be implemented before further improvements are made to decrease seepage. In the meantime, a modeling analysis of the various aspects of seepage through the dam was conducted to evaluate effective / ineffective remedial measures and guide appropriate monitoring programs. It was further decided to perform a three-dimensional analysis since Fordyce Dam contains several such features that would induce 3D or non-uniform flow patterns including its location in a relatively narrow valley founded partly on bedrock and streambed alluvium with a non-uniform concrete cutoff wall and the presence of bedrock joints along the left abutment originating from an old quarry upstream of the dam (PG&E, 2002).

The three-dimensional flow model for investigating seepage through Fordyce Dam is developed from a previous 2D modeling study of the section that passes through the alluvial channel using the finite-element code SEEP/w (Geomatrix, 2001) which used the best available estimates for in situ hydraulic conductivity of each material comprising the dam – values which have been reviewed and accepted by PG&E. The model however could only account for around 4 cfs seepage (of the approximately 25 cfs) at full reservoir

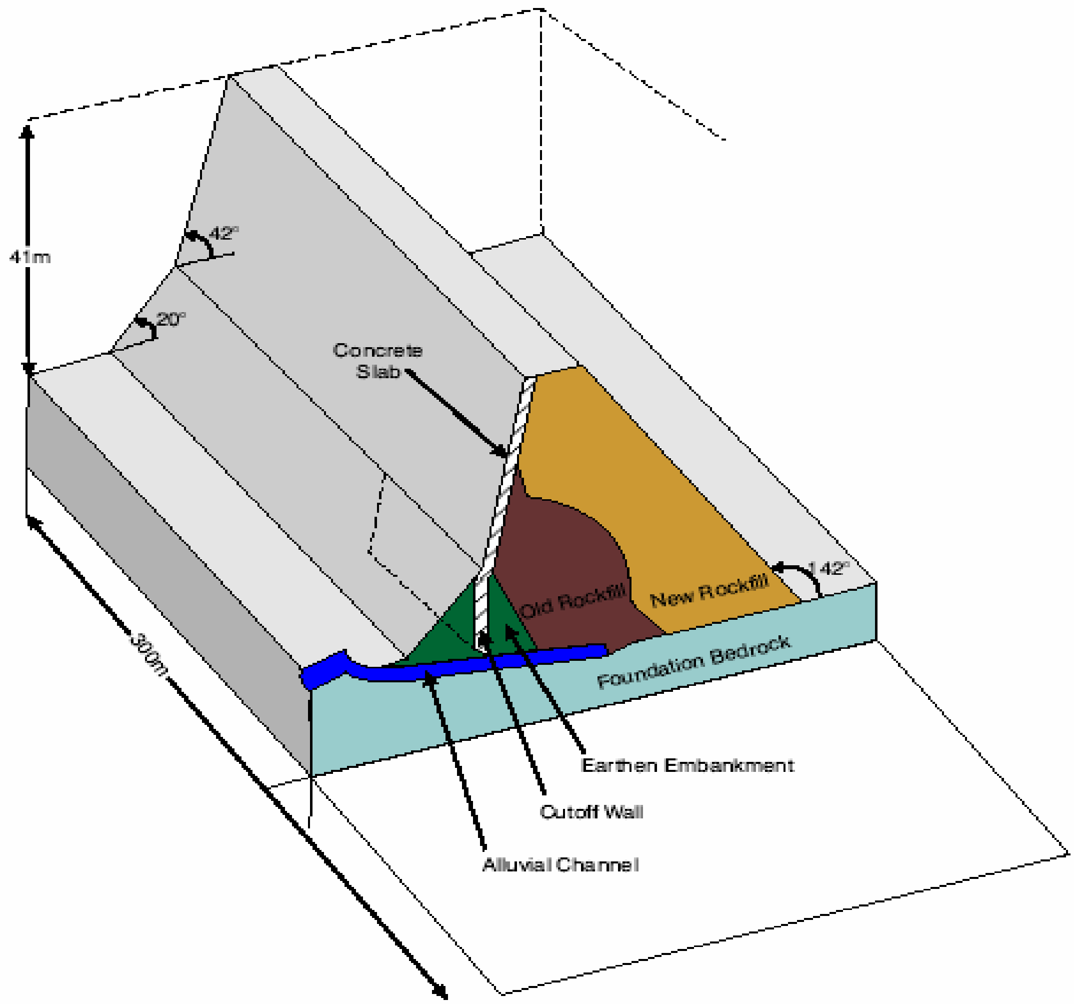


Figure 1 Layout and sectional configuration of Fordyce Dam

conditions, with most of the flow occurring through the alluvial channel section. Sensitivity analyses on critical parameters (increasing the conductivity of the concrete slab by a factor of hundred to account for possible leakage from the joints in the concrete slabs, and increasing the permeability of the alluvial channel by a factor of five because of the noted significant impact of the channel) could increase this number to around 14 cfs and it was suggested that measured flow rates may not be an accurate indication of actual flow through the dam due to other contributing factors such as leakage from the outlet valve and flow from other downstream sources such as surface runoff. However, this inaccuracy could not account for the large differences between estimated and measured flow rates and it was concluded that the difference may be attributed to additional seepage paths at the dam perhaps through fractured bedrock underlying the abutments, or leakage around or through the old outlet structure – conditions that could not be modeled with the 2D model being analyzed. The 3D model was first compared with its 2D SEEP/w counterpart to ensure that similar results were being produced for similar simulated conditions. A sensitivity analysis was then conducted to evaluate the various components contributing to total seepage, to determine their relative contribution and uncertainty to total flow. The upstream concrete face, concrete cutoff wall, earthen embankment, bedrock, streambed alluvium, and bedrock joints along the left abutment were evaluated for their contributions towards the expected theoretical seepage through Fordyce Dam. Seepage quantities, water pressure conditions and water levels within the dam were evaluated for their effects on seepage and reducing model uncertainty. From these evaluations, additional field and modeling investigations can be determined that will help guide further repair options and sequencing.

## MODEL CONSTRUCTION

The MODHMS (MODFLOW-based Hydrologic Modeling System) finite-difference code was used for this study due to its flexibility and capability in handling the required flow physics. MODHMS is based on the popular USGS groundwater flow modeling code MODFLOW and includes several additional modules – the pertinent ones for this project include state-of-the-art robust and efficient solution schemes for large 3D porous medium flow problems with high heterogeneities (including robust drying / rewetting schemes, Newton Raphson linearization and efficient iterative sparse matrix solvers), capability of handling the required flow and boundary conditions, and ability to easily process input and output data-files with the ViewHMS processor. Further, it allows use of curvilinear geometries for more complex analyses, therefore providing the flexibility of finite element grids without the extra computational burden. Finally, besides robust unconfined simulation capability, a robust unsaturated zone flow capability provides flexibility to undertake more complex analyses if / when needed. Details of its governing equations and solution schemes of MODHMS are provided in Panday and Huyakorn (2004).

An areally rectangular grid was used for this study – the curvature of the dam's face is neglected due to its lack of significance for a seepage analysis. Figure 2 shows a section through the active finite-difference grid and Table 1 provides the associated material properties (same as the values used in the earlier 2D SEEP/w study) for the foundation

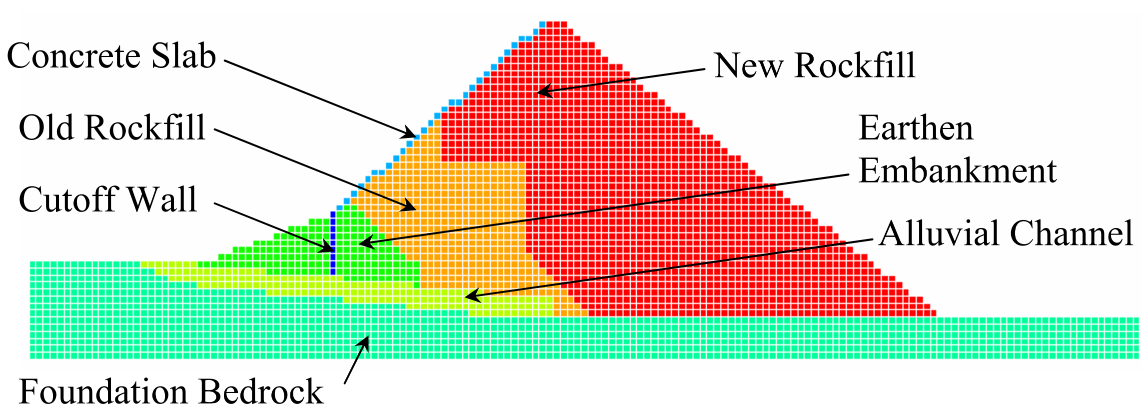


Figure 2 Active domain grid and materials assigned to the 3D model

bedrock, earthen embankment, cutoff wall, alluvial channel (only the middle 66 ft of the old Fordyce Channel), old and new rock-fills, and the concrete slab within the cross-section. Boundary conditions supplied to the domain include a constant head of 6337 ft along the upstream face of the dam (representing full reservoir conditions) with a tail-water elevation of 6202 ft and a seepage face condition along the downstream face of the dam for steady-state seepage simulations to note the water profile and seepage flux through the dam.

Table 1 Hydraulic Properties of the Materials

| Material | Hydraulic Conductivity | Vertical Anisotropy |
|---|---|---|
| New Rock-fill | $5 \times 10^{-2}$ m/s | 2 |
| Old Rock-fill | $1 \times 10^{-2}$ m/s | 3 |
| Earthen Embankment | $1 \times 10^{-5}$ m/s | 4 |
| Foundation Bedrock | $1 \times 10^{-6}$ m/s | 1 |
| Channel Alluvium | $3 \times 10^{-3}$ m/s | 10 |
| Concrete Cutoff Wall | $1 \times 10^{-8}$ m/s | 1 |
| Concrete face | $1 \times 10^{-8}$ m/s | 1 |

## RESULTS

The base case scenario is the same as the 2D SEEP/w simulation. Aside from the presence of the alluvial channel and concrete cutoff wall for only small segments of the dam section, the properties and geometries are uniform along the length of the dam. The water table profile within the dam and along a section passing through the middle of the alluvial channel is located on the zero pressure contour line shown in Figure 3. This figure is similar to the pressure contours of the 2D SEEP/w study indicating that flow through the middle section of the dam containing the alluvial channel is well represented by the earlier 2D model. The seepage flow calculated for the base case is 5.25 cfs which is similar to the value evaluated by the 2D SEEP/w study of approximately 4 cfs and which grossly underestimates the field measured values of around 25 cfs.

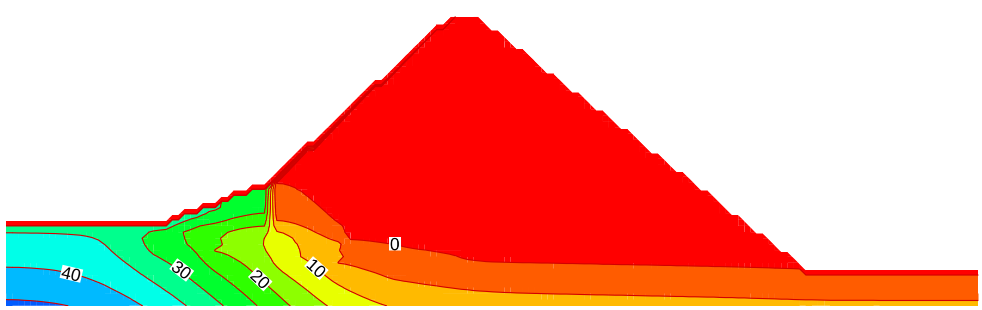


Figure 3 Pressure profile through the middle section for the base case simulation.

A sensitivity study was conducted to various parameters of the dam to evaluate the reason for the small calculated numbers as compared with measured values, and to estimate what would be required of the parameter to achieve the higher measured value. Increasing the hydraulic conductivity of the concrete slab and cutoff wall by factors of 5, 10, 20 and 25 increases the seepage to 9.47 cfs, 13.56 cfs, 22.37 cfs and 26.65 cfs. Increasing the hydraulic conductivity of the alluvial channel by a factor of 10 increases the seepage flux to 34.65 cfs. These two parameters are the most important uncertainties of this evaluation and better estimates of these parameters should help in better understanding of the seepage flows through the dam. Increasing the hydraulic conductivity of the foundation rock by factors of 2 and 5 show little change (0.18 cfs and 0.791 cfs respectively) in the flux thereby indicating that the foundation rock conductivity is not sensitive to the simulation within its estimated bounds. Similar seepage flux changes were noted for increasing the hydraulic conductivity of the earthen embankment by factors of 2 and 5 (0.206 cfs and 0.82 cfs respectively). Sensitivity studies are not performed for the rockfill materials, because the water-table is noted to lie mainly within the earthen embankment, and within the concrete face. The rockfill is therefore not a critical parameter in preventing seepage from the dam structure or underlying foundation.

Other sensitivity analyses were conducted to test various other features that may be present in the dam. Field investigations have indicated that there is a gap present between the concrete wall within the earthen embankment and the slab face and therefore, this gap is examined in a sensitivity simulation. The seepage from the dam increases to 6.91 cfs when the gap is simulated – an effect that cannot explain the large difference between simulated and measured seepage fluxes. However, it is noted that a combination of this gap and higher hydraulic conductivity value for the earthen embankment (by a factor of 10) increases the seepage from the dam to 23.16 cfs – a value close to measured conditions. Another simulation investigates the effect of the actual cutoff wall as depicted in drawings of the dam. The actual cutoff wall exists only in the middle portion of the dam and varies as shown in Figure 4 as opposed to the idealized rectangular section of the base case that extended the length of the dam. Seepage through the dam increases to 6.48 cfs when the adjacent material is provided with bedrock properties and to 7.53 cfs when the adjacent material is provided earthen embankment properties, indicating that the effect, though present, is not significant by itself, and the earthen embankment itself provides sufficient resistance to flow.

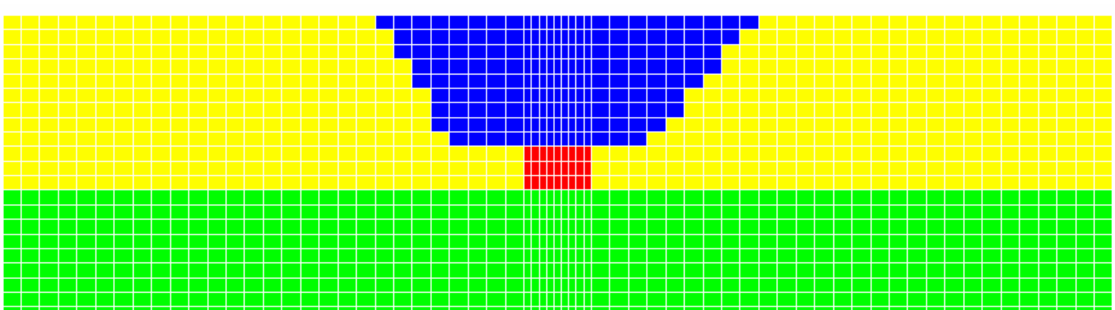

Figure 4 Section through Fordyce Dam showing actual cutoff wall geometry.

The next set of sensitivity simulations examines the effect of possible seepage paths through joints and crevices in the fractured bedrock which probably originate in the reservoir at an old quarry site upstream of the left abutment and finally emerge at the left abutment (PG&E, 2002). The bedrock joints are typically spaced 0.2 ft to 2 ft and have typical apertures of less than 0.1 inch. Assuming laminar flow between parallel plates, the conductivity of such fractures can be derived as (Roberson and Crowe, 1985):

$$K_f = \rho g B^3 / 12\mu \qquad (1)$$

Where $\rho$ is the density of water, g is gravity, B is the aperture spacing, and $\mu$ is the viscosity of water. The medium conductivity can then be computed as

$$K = K_f \ \phi_f \qquad (2)$$

Where $\phi_f$ is the fracture porosity ($\phi_f$ = B/L where L is the fracture spacing). Using (1) and (2) and for fracture parameter values of the bedrock as given above, the hydraulic conductivity of the fractured bedrock varies from 5.58 x $10^{-5}$ m/s to 5.58 x $10^{-4}$ m/s. When material properties of the bedrock were changed to 5.58 x $10^{-4}$ m/s (at the higher end of estimated values) for 20 m along the left abutment of the dam, the seepage from the dam increased to 10.32 cfs; when material properties of the bedrock were changed to 5.58 x $10^{-4}$ m/s for 100 m along the left abutment of the dam, the seepage from the dam increased to 21.19 cfs which is close to the measured flux through the dam. Fracturing from the old quarry is not noted to be as extensive as 100 m into the dam section and therefore this factor too, alone, is not the cause for the reduced calculated seepage conditions.

Figures 5, 6, and 7 show the pressure contours within the dam and along a section passing through the middle of the alluvial channel for the cases with hydraulic conductivity of the concrete slab and cutoff wall increased by a factor of 25, the case of hydraulic conductivity of the alluvial channel increased by a factor of 10, and the case of a gap between the concrete wall and the slab face with earthen embankment properties increased by a factor of 10. All three cases provide seepage fluxes that are within measured ranges for Fordyce dam. It may be noted that the water levels are different for the three cases, and therefore further explorations may try and determine water pressure profiles through the dam (or water levels at key locations) which may be compared with these simulated results to determine the representative significant parameters and reduce model uncertainty. Similarly, comparing pressure contours through the left abutment of the dam for the cases of fracturing and no fracturing can help evaluate the fracturing.

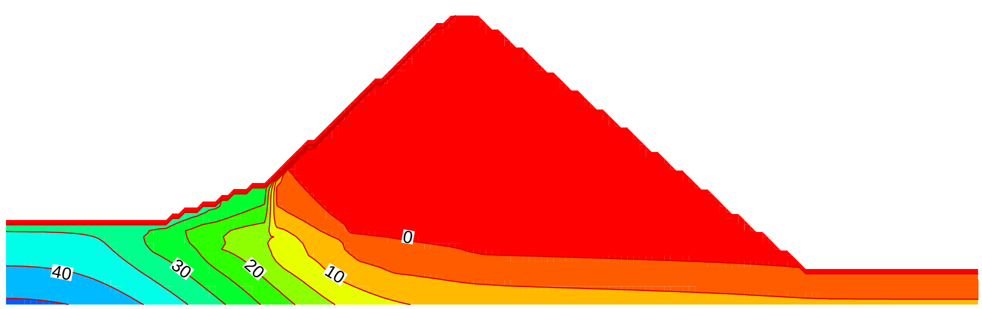


Figure 5 Pressure profile through the middle section for the case of hydraulic conductivity of concrete slab and cutoff wall increased by a factor of 25.

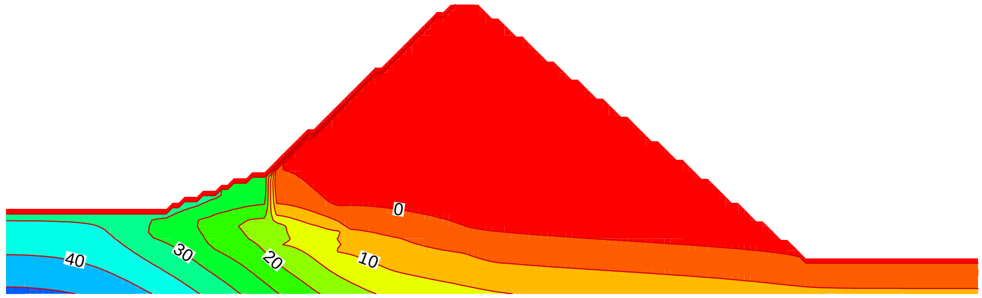


Figure 6 Pressure profile through the middle section for the case of hydraulic conductivity of alluvial channel increased by a factor of 10.

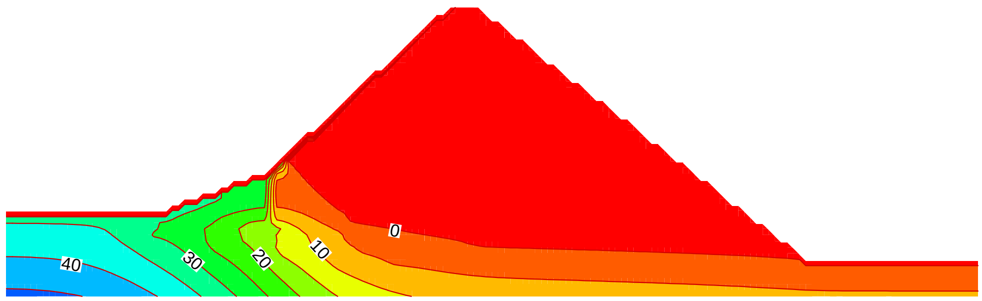


Figure 7 Pressure profile through the middle section for the case of gap between concrete wall and slab face with earthen embankment conductivity increased by a factor of 10.

A final set of simulations was performed for the cases which have seepage fluxes that are close to measured conditions. This simulation set examines seepage from the dam under lower upstream head conditions, with an upstream water level of 6240 ft. Resulting seepage values are 3.4455 cfs for the case with concrete slab and cutoff wall conductivities increased by a factor of 25; 8.1153 cfs for the case with alluvial channel conductivity multiplied by a factor of 10; 1.5447 cfs for the case with a gap between the concrete wall and the slab face with earthen embankment properties increased by a factor of 10; and 4.8805 cfs for the case with fracturing within the bedrock along 100 m adjacent to the left abutment of the dam. Thus, seepage for these 4 cases is very different from each other when the upstream water level of the dam is low, even though they have similar seepage values when the upstream water level is full. Therefore further explorations should try and determine seepage flows for low upstream water level conditions, to identify the significant parameters that cause the observed seepage and reduce uncertainty on the causes of seepage through the dam.

## CONCLUSIONS

A model was constructed for three-dimensional seepage analysis through Fordyce Dam. The model provides similar results to a 2D modeling analysis when both models have similar assumptions, giving seepage through the dam of around 5.25 cfs. Measured seepage of around 25 cfs can be achieved if the concrete slab and cutoff wall hydraulic conductivities are 25 times higher than initial estimates or if the alluvial channel hydraulic conductivity is 10 times higher than initial estimates, or if a gap is present between the concrete wall within the earthen embankment and the slab face along with a 10 times higher estimate for the earthen embankment's hydraulic conductivity, or if bedrock fracturing were present along the left 100 m of the dam. Very likely, it is a combination of these factors, in lesser amounts, that causes the measured seepage through the dam. An analysis of the pressure profiles through the dam sections shows different profiles for the different factors and therefore, a monitoring program may be setup to investigate which factor provides the most appropriate behavior. A field monitoring program may also investigate dam seepage under different upstream water-level conditions to further reduce uncertainty among these alternatives since they all result in different seepages under low water conditions. Finally, it should also be noted that the concrete face shows different levels of deterioration at different heights (with most of the deterioration occurring near the top of the dam) and including this into future modeling studies (for seepage analysis before and after repairs) would further enhance the results and reduce model uncertainty. After factors affecting seepage are delineated with lesser uncertainty, the model may be used to prioritize among repair and maintenance alternatives by taking into consideration parameters that cause the largest seepage. The views expressed herein do not necessarily represent the views of the Federal Energy Regulatory Commission or of the United States of America.

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