Seismic Performance Evaluation of Concrete Gravity Dams - A Case Study of Pine Flat Dam

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SUMMARY:
This paper summarises the research on performance assessment of concrete gravity dams. The assessment methodology is based on the stress demand-capacity ratio (DCR) and the cumulative inelastic time duration as two performance indices.The performance assessment methodology was applied on Pine Flat Dam in California as a case study. Probable seismic damages of the case study at three distinct ground motion hazard levels were quantitatively assessed using response history analysis by EAGD computer code. It was concluded that the design guidelines used to proportion the dam dimensions were adequate; the dam exhibited no damage at Operating Basis Earthquake (OBE) level. At Maximum Design Earthquake (MDE) and Maximum Credible Earthquake (MCE) levels some tensile cracking occurred but the level of cracking was deemed acceptable with no possibility of failure.

Keywords: Concrete Gravity Dam, Seismic Performance Evaluation, Pine Flat Dam, DCR, Inelastic Time Duration

1. INTRODUCTION

Seismic safety of dams is particularly important considering catastrophic economical consequences of operation disruption. Although there have been no reported cases of complete concrete dam failure, past experience shows that concrete dams may be damaged or cracked seriously through seismic excitation (Hinks and Gosschalk (1993); Zhou and Lin (1992)). Typical examples of dams that have suffered serious fracture problems in the past are: 1) Koyna dam, India (1967), 2) Hsingfengkiang dam, China (1962) and 3) Sefid-Rud dam, Iran (1990) (Valliappan, Yazdchi and Khalili (1996)).

Seismic performances of existing and new dams are determined by linear and nonlinear analysis (El-Aidi and Hall (1989a, b); Ghaemian and Ghobarah (1999); Ariga et al. (2001)). The conventional seismic performance evaluation approach is based on linear theory where it enforces compressive and tensile stress capacity-demand ratios of 1.5 and 1.0, respectively. However, in practice some stress excursions above the tensile strength of the concrete have been considered acceptable based on engineering judgment (USACE 2003).

The seismic coefficient method is a convenient initial step for estimating the global stability of a concrete gravity dam. In this method it is assumed that the dam acts as a rigid body, thereby, its inertia force acts in the horizontal direction and on its center of mass. Such representation of the dam often underestimates the magnitude of the actual inertia actions because of the amplification effects associated with the flexibility of the dam structure. Despite this caveat, the seismic coefficient method is a convenient initial step for estimating the structural global stability of concrete gravity dams, and it has been often used as a tool to decide if more rigorous dynamic analyses should be undertaken.

Estimation of dynamic stress responses is typically done using a simplified response spectrum approach as developed by Chopra (1978), and Fenves and Chopra (1986). In those cases where it is necessary to obtain a more specific assessment of the expected seismic performance, this initial approach is typically followed by linear time-history analyses. The quantification of the time-varying characteristics of the relevant response quantities provides important information regarding the expected behavior under seismic loadings.

Recommendations for seismic evaluation using time-history procedures are provided in USACE Engineer Manual 1110-2-6051 (2003). This manual recommends a systematic interpretation of linear time-history results and it provides performance criteria for quantitative estimation of the level of damage. To quantify the magnitude and spatial distribution of the resulting damage, it is necessary to determine the actual response of the dam using nonlinear time-history analysis. This approach is mainly based on the demand capacity ratio (DCR), which is defined as the ratio between the maximum principal stress and the tensile strength of concrete and inelastic cumulative duration, which is defined as the total duration of stress excursions that exceed a certain level of DCR.

If the predicted performance falls below the specified limit line (see Fig. 1), the seismically induced damage is expected to be minor or negligible and the results of the linear time-history analysis would be sufficient to characterize the performance. Otherwise, the level of structural damage is expected to be severe, and the accurate estimation of its actual extent of damage and consequences should be carried out using nonlinear models. Therefore, these guidelines provide a set of standard criteria that, along with the proper engineering judgment, allow the analyst to ascertain whether a nonlinear dynamic analysis is needed to complete the seismic evaluation.

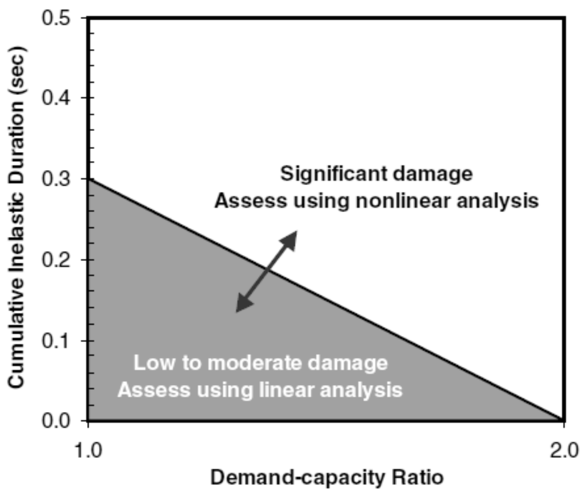

Figure 1. Performance/damage acceptance criteria for concrete gravity dams (USACE (2003))

In this paper, the results of seismic performance and safety evaluation of a concrete gravity dam (Pine Flat dam), located in California, USA (Fig's 2 & 3), based on the USACE guidelines are presented.

Probable levels of seismic damages of Pine Flat dam induced by three levels of ground motions (OBE, MDE and MCE) have been quantitatively estimated according to the USACE guidelines. For this, the computer code, EAGD-84 was utilized for linear time history analysis of two-dimensional finite element model of the dam. The computer code considers the factors that influence significantly the analysis of concrete gravity dams such as dam-water interaction, wave absorption at the reservoir boundaries, water compressibility and dam-foundation rock interaction (Fenves and Chopra (1984)).

2. ANALYSIS METHODOLOGY

Quantitative estimation of probable level of seismic damage induced by the three specified ground motions is carried out according to the USACE guidelines for linear-elastic time-history dynamic analysis of concrete dams. The methodology, which is based on the work by Ghanaat (2002), can be effectively used to establish a range of validity for linear elastic analyses results. This methodology is based on the consideration of performance indices such as stress demand-capacity ratio (DCR) and inelastic cumulative time duration.

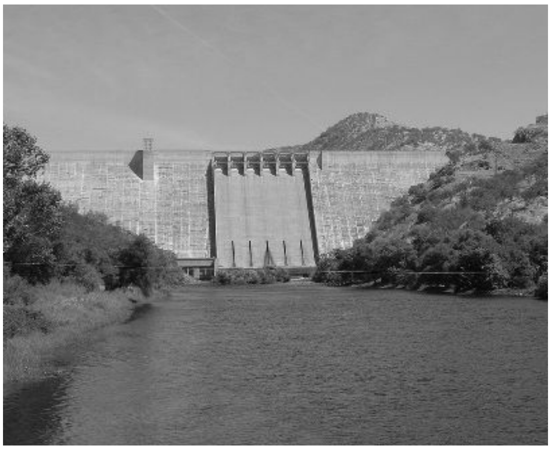

Figure 2. Pine Flat Dam, California, USA.

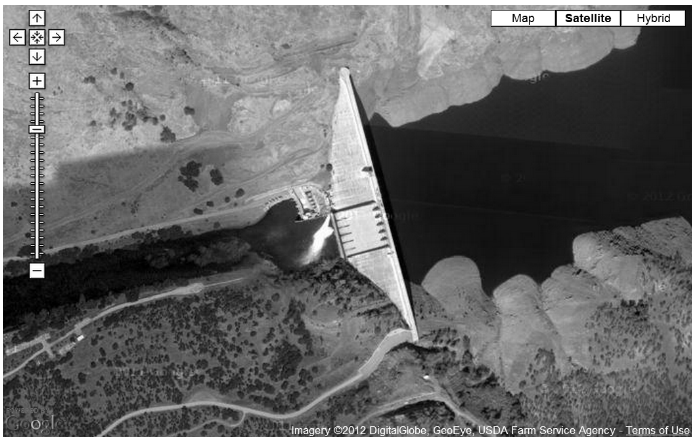

Figure 3. Satellite image of the Pine Flat Dam

If the computed DCR values are less than or equal to 1.0, then the dam response is considered to be within the linear elastic range with little or no possibility of damage. In this case results from the linear analysis contain all relevant information regarding the dynamic response of the dam. If some DCR values exceed 1.0, then linear response of the system is considered to be acceptable only if spatial distribution of overstressed regions does not exceed 15 percent of the dam area and the corresponding cumulative duration of stress excursions falls below a curve indicating limit performance (Fig. 1). In this case, the level of nonlinear response or cracking is deemed acceptable with no possibility of failure. Also, results from the linear time-history analysis still provide sufficient information to characterize the response of the system. If these conditions are not met, then the level of expected damage should be considered as severe. In these situations a nonlinear time-history analysis may be required, especially if the fundamental period of the dam falls in ascending region of the response spectra (Ghanaat (2004)).

3. PINE FLAT DAM MODEL AND PROPERTIES

Pine Flat concrete gravity dam is 97 m wide at the base. The tallest, non-overflow monolith is 122 m high. The two dimensional finite element idealization of this monolith, shown in Figure 4, consists of 1224 quadrilateral elements with 1300 nodal points.

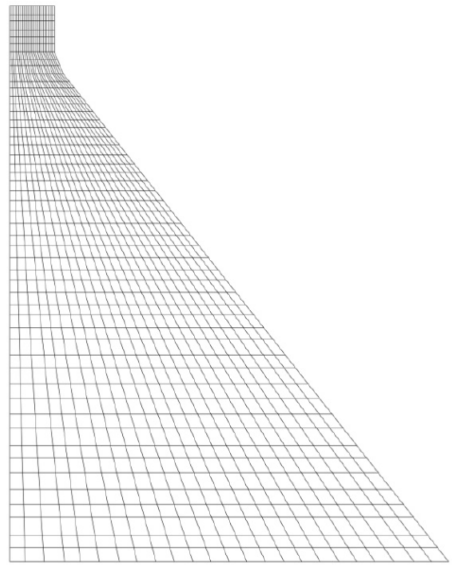

Figure 4. Finite elements model of Pine Flat Dam

The concrete material used in the dam is assumed to be homogeneous, isotropic, linear elastic with the following properties obtained, in part, from forced vibration tests of the dam: Young's modulus of elasticity E_s = 22.4 GPa, unit mass = 2395 kg/m^3, and Poisson's ratio = 0.2.

The foundation-rock region supporting the dam monolith is idealized as a homogeneous, isotropic, viscoelastic half-plane. The assumed material properties of the foundation rock are: Young's modulus of elasticity E_f = 22.4 GPa, a value which may be reasonable for the fissured granites and basalts at the site; unit mass = 2490 kg/m^3, and Poisson's ratio = 0.33.

The water in the reservoir impounded by the dam is idealized by a fluid domain that extends to infinity in the upstream direction and has a constant depth of 116 m. This water level corresponds to a full reservoir condition. The water is assumed to be compressible with a unit mass of 1000 kg/m^3. The material underlying the upstream reservoir may consist of highly variable layers of exposed bedrock, alluvium, silt and other sedimentary material. The value of wave reflection coefficient α, selected based on their actual properties and not on properties of the foundation rock, characterizes the reservoir bottom materials. Because there is no data available on the properties of the reservoir bottom materials upstream of Pine Flat Dam, a wave reflection coefficient $\alpha = 0.5$ is arbitrarily selected for the analysis.

The ground motion recorded at Taft Lincoln School Tunnel during the Kern County, California Earthquake of 21st of July 1952, was selected as the free-field ground acceleration for analysis of Pine Flat dam and used as an OBE level of ground motion. Two horizontal (transverse to the axis of the dam) and vertical components of the recorded ground motion were applied. The time history of these two components are shown in Fig. 5 (PGA of horizontal component = 0.18g and that of vertical one = 0.15g). The ground motion was scaled to two other levels of ground motion (MDE and MCE with PGA's of 0.27g and 0.45g) and was used in the analyses.

4. RESULTS AND DISSCUTION

The seismic performance of the Pine Flat dam is evaluated using the linear time-history analyses results. The analysis showed no elements stressed over the tensile strength of concrete, see Fig. 6, and therefore according to the performance criteria, the damage is considered acceptable with no possibility of failure because the performance curve is below the limiting line.

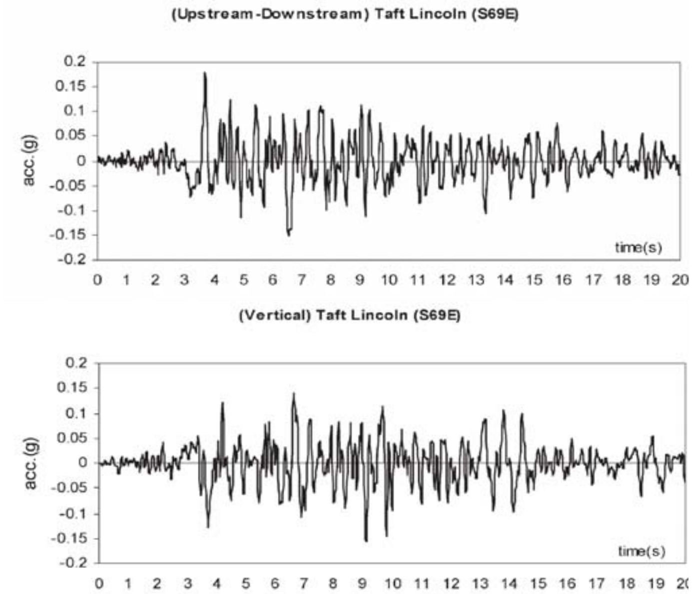

Figure 5. Ground motion of Kern County, California, Earthquake of 21 st of July 1952, recorded at Taft Lincoln School Tunnel (Ghanaat (2004))

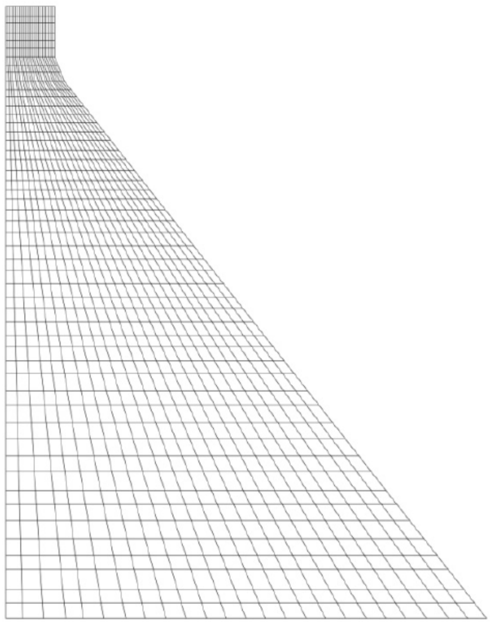

Figure 6. No elements is being overstressed due to OBE ground motion level

Figure 7 shows the overstressed elements at the MDE level (0.27g). At this earthquake level, the maximum principal stresses of two elements at the heel of the dam exceed the tensile strength of concrete. Fig's 8 & 9 show the time history of principal stresses at the heel of the dam and corresponding performance curves of the overstressed elements at the MDE level at the heel of Pine Flat dam.

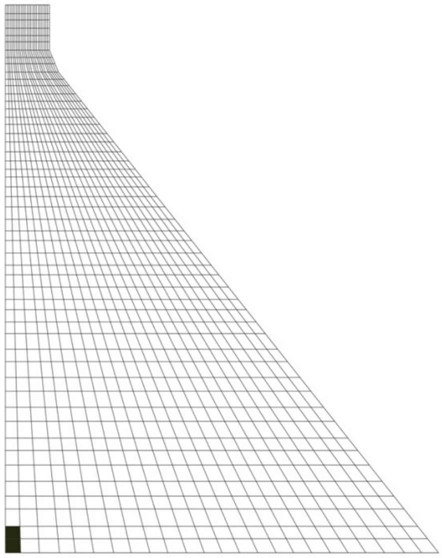

Figure 7. Overstressed elements due to MDE ground motion level

It is expected from the performance curves that some tensile cracking will occur but its level is deemed acceptable with no possibility of failure.

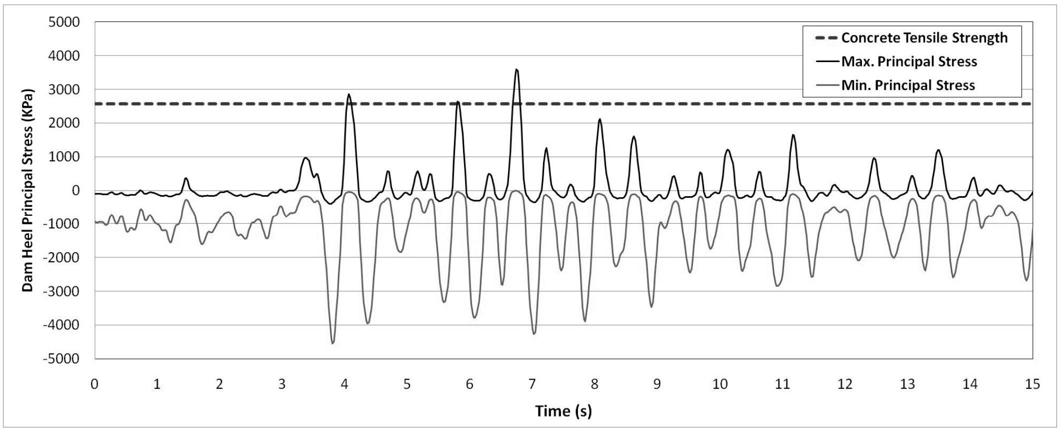

Figure 8. Principal stress of the heel elements due to MDE ground motion level

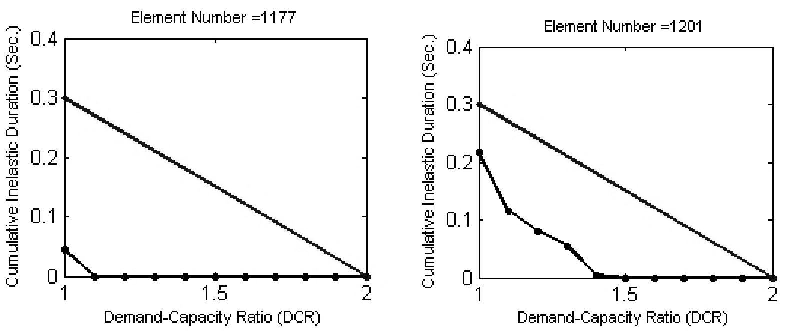

Figure 9. Performance curves of the overstressed elements at the heel due to MDE ground motion level

At the MCE ground motion level (0.45g), as shown in Fig. 10, the overstressed elements have increased. The time histories of principal stress and corresponding performance curves at the MCE level of the upstream elements at the points of slope change and heel of Pine Flat dam are shown in Fig's 11 to 13.

According to the performance curves, it is expected that some tensile cracking would occur but the level of cracking is still considered acceptable with no possibility of failure. However at the MCE level, the dam will experience higher level of damage, as compared with MDE level, but yet according to the proposed criteria the dam is repairable.

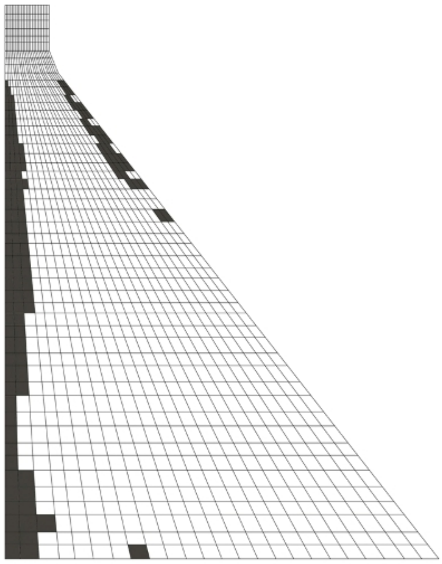

Figure 10. Overstressed elements due to MCE ground motion level

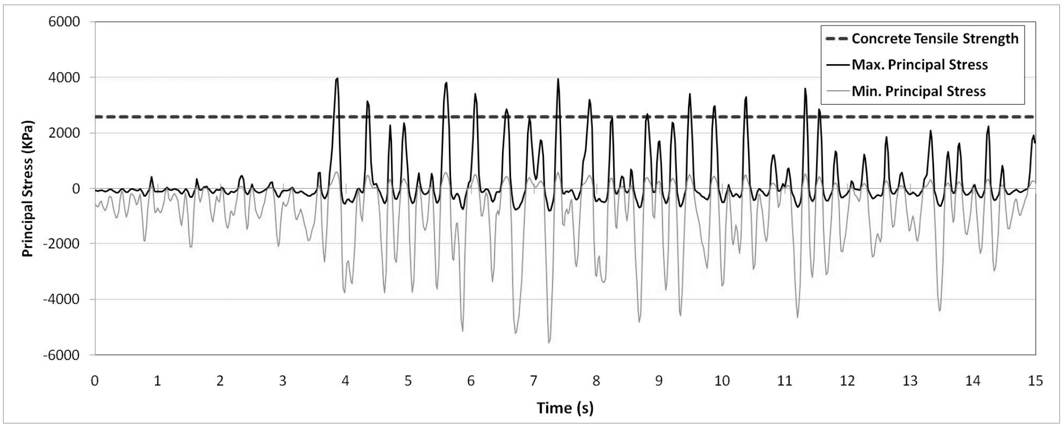

Figure 11. Principal stress time history of the upstream element at the point of slope change due to MCE ground motion level

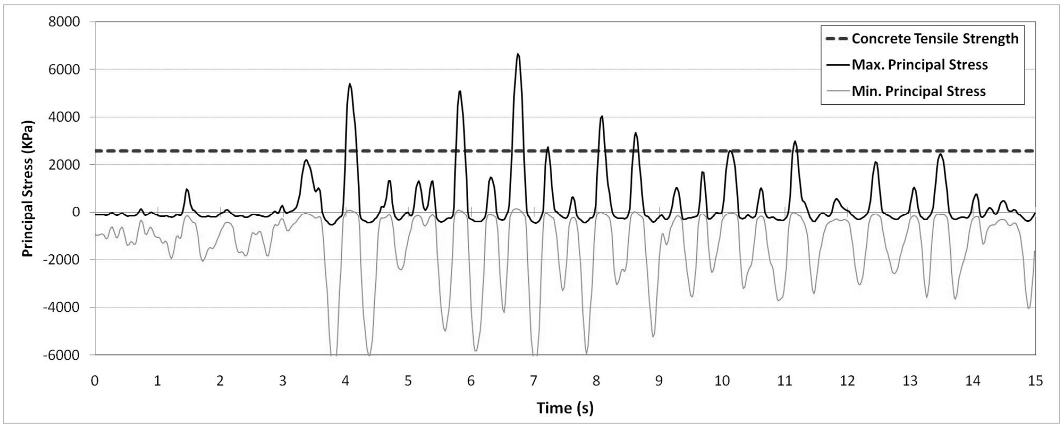

Figure 12. Principal stress time history of the upstream element at the heel due to MCE ground motion level

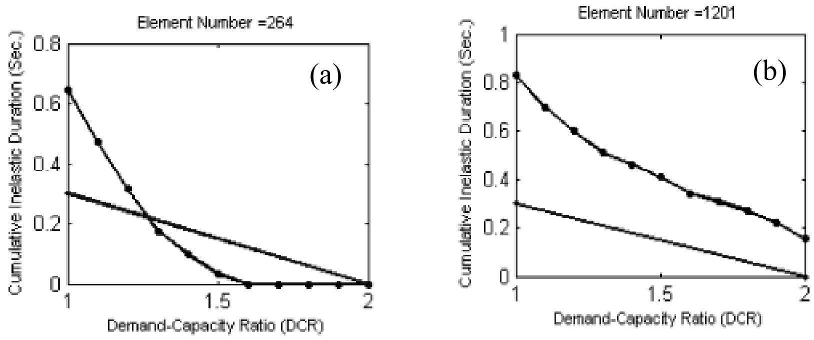

Figure 13. Performance curves of upstream elements at (a) slope change and (b) heel of the dam due to MCE ground motion level

Although for some DCR values of these elements of the dam, the cumulative inelastic time duration exceed the limiting value, but it is not considerable at all.

5. CONCLUSIONS

Seismic performance and safety of a concrete gravity dam, Pine Flat dam of California, USA, was evaluated in this study. It was concluded, from the linear analyses results, that at the OBE level (0.18g), the damage is considered acceptable with no possibility of failure. At MDE and MCE levels (0.27g and 0.45g, respectively), some tensile cracking occurred but with no possibility of failure. Even though the extent of damage is higher at MCE level than that of MDE level, but still the dam is reparable according to the proposed criteria.

According to the proposed performance criteria, the selected ground motions did not produce significant nonlinear deformation in Pine Flat dam, and so the said guideline did not require nonlinear analysis to be performed.

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