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Risk-Informed Levee Erosion Countermeasure Site Selection And Design In The Sacramento Area

Part 2: Probabilistic Numerical Simulation Of Bank Erosion

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ABSTRACT

USACE partnered with the United States Department of Agriculture, Agricultural Research Service, United States Geological Survey, and Texas A&M University to evaluate the erodibility of the river banks and levees to inform probabilistic numerical simulations using the Bank Stability and Toe Erosion Model (BSTEM). This paper, the second of two parts, addresses processing the collected data to inform inputs for probabilistic bank erosion estimates in BSTEM. Measuring the intrinsic soil properties for BSTEM is discussed in part one. Soil critical shear stress and soil erodibility coefficients were calibrated by Unified Soil Classification soil type to observed erosion on the American River. Adjustments were made in the probability density functions for these parameters to reflect field-measured variability and carry forward the reduction in error achieved during calibration. The resulting calibrated values were tested at additional sites, validating the resulting critical shear stress and soil erodibility coefficient values and probability density functions for more robust probabilistic bank erosion estimates using BSTEM.

INTRODUCTION

Levees along the lower portion of the American River (LAR) and the Sacramento River (SAC) provide flood damage risk reduction for the Sacramento urban area, one of the highest flood risk cities in the United States of America (Figure 1). The United States Congress has allocated funds for the United States Army Corps of Engineers (USACE) to reduce the likelihood of an erosion related failure of the American and Sacramento River levees, a primary risk driver for these levees. The American and Sacramento Rivers provide valuable habitat and experience heavy recreation use. Selecting and designing sites for erosion countermeasures need to consider impacts to habitat and recreation while meeting flood risk reduction objectives. While portions of the levee system are immediately adjacent to the main river channels and experience high river flow velocities, others are set back variable distances from the floodplain but could still be at risk from progressive bank erosion. Therefore, probabilistic estimates of bank erosion for future large floods are beneficial for risk-informed erosion countermeasure site selection and informing erosion countermeasure design. This paper discusses the processing of the collected soil data to inform inputs for probabilistic bank retreat estimates in BSTEM, which is the second of two parts. The first part addressed the measurement of the intrinsic erosion and geotechnical properties of the soil.

BANK EROSION

Bank erosion is a complex series of physical processes that result in bank retreat. The amount of bank retreat is often most sensitive to the interaction of fluvial erosion and slope failures. Fluvial erosion occurs when the applied erosive forces from flowing water entrain and transport the bank material away. Slope failures occur when the weight of the soil mass of the eroded bank (and other material on the bank) and any external forces, such as earthquakes, exceed the ability of the soil to resist the forces and the soil mass moves down the slope. For slope failures the soil resistance threshold is modeled collectively as the ratio of the combined resisting forces to the driving forces, which is the factor of safety (FOS). A FOS less than one indicates a slope failure occurs. In bank erosion, fluvial erosion can steepen the bank leading to slope failures.

Soil has an intrinsic resistance to the shear stress applied by flowing water, due to soil gradation density, consolidation, cohesion, and the presence or absence of riparian vegetation root structure. This causes the soil to resist erosion up to a certain threshold. This threshold is often represented as a critical shear stress (Lagasse et al. 2009; Wilcock et al. 2009) or a critical velocity (Briaud and Montalvo-Bartolomei 2016). While Shield's diagram (Yang 1996) may be useful to help define the incipient motion threshold for cohesionless material in the bank or deposited at the bank toe, for fine soils, particle interactions become more important and estimates of erosion thresholds are determined from direct soil measurements or from observed bank retreat (Briaud and Montalvo-Bartolomei 2016). Once this threshold is exceeded, the rate of erosion depends on the intrinsic properties of the soil, often represented as an erodibility coefficient. Fluvial erosion is often represented using the excess shear equation: $E = k_d(\tau_o - \tau_c)$, where E = erosion rate (L/T), k_d = soil erodibility coefficient (L^{2}T/M or L^3/FT), τ_0 = shear stress exerted by the flowing water on the bank M/LT^2 or F/L$^{2)}$, and τ_c = soil critical shear stress (M/LT^2 or F/L^2). BSTEM utilizes the excess shear equation to evaluate lateral migration of the bank surface by fluvial erosion. The equation requires a representative critical shear stress, erodibility coefficient, and an estimation of the (grain) shear stress acting on the soil surface (BSTEM uses an effective Manning's n value that includes the effects of variations in bank topography and vegetation).

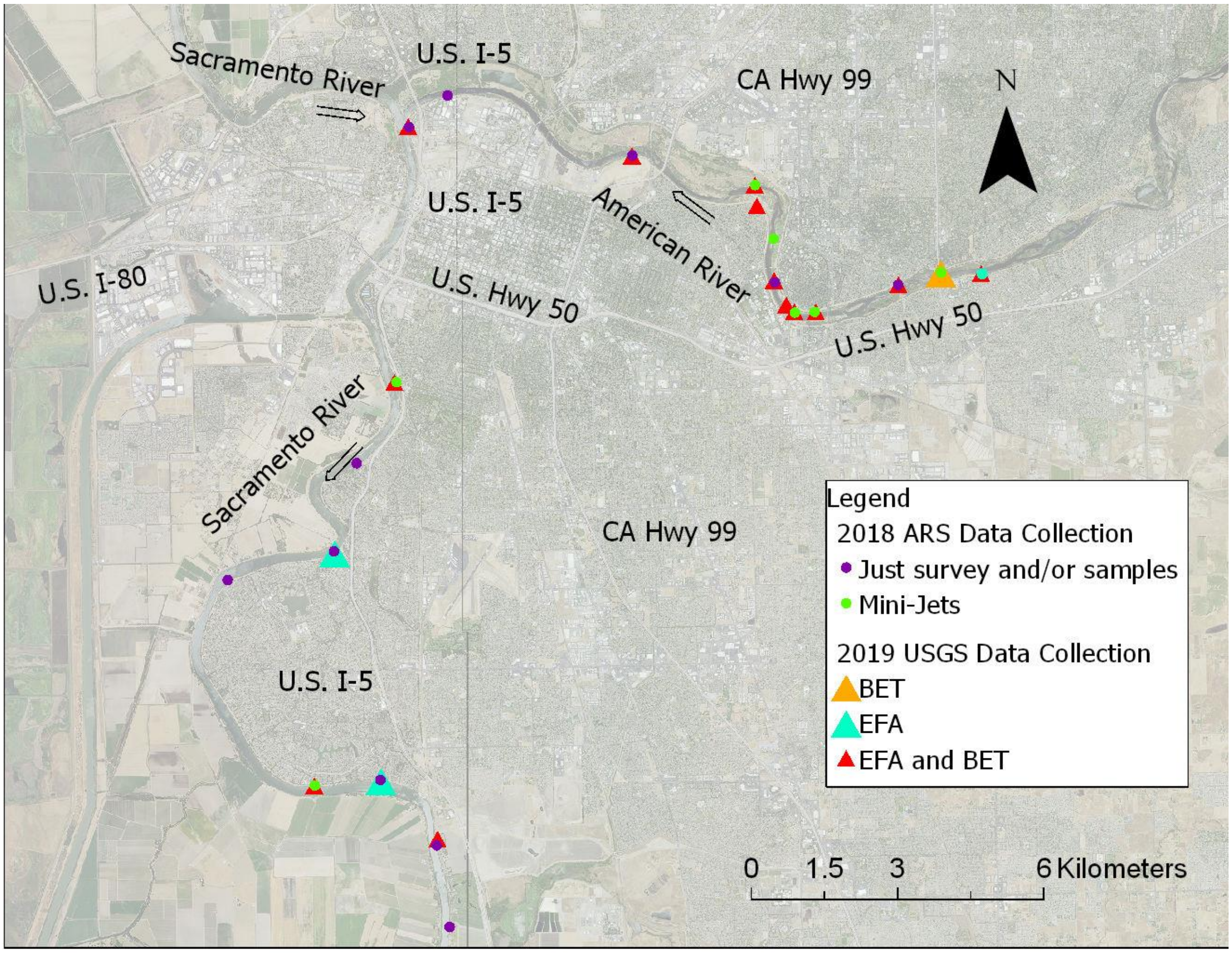

Figure 1. Data collected in 2018/2019 around Sacramento, CA in the area of interest for bank protection. BET – Borehole Erosion Test; EFA = Erosion Function Apparatus test, and mini-JET – mini Jet Erosion Test.

PROBABILISTIC NUMERICAL SIMULATION OF BANK EROSION

The ranges of the critical shear and erodibility coefficient tested on the American and Sacramento rivers were utilized for the BSTEM modeling, instead of relying on ranges of published values representative of a wide range of fluvial rivers (Fischenich 2001) because of the heterogeneity of fluvial soils. Use of published literature values may be acceptable for many projects if appropriate conservative values for the critical shear and erodibility coefficients are used for the risk associated with the project. However, there is uncertainty and variability with soil erodibility parameters that is not trivial and selecting a single representative value is difficult. Because of this, it is useful to calibrate to observed erosion for site-specific conditions such as proposed by Briaud and Montalvo-Bartolomei (2017).

To help identify the bank erosion risk, and specifically the fluvial erosion potential at the bank toe, it was desirable to collect a larger sample size to better evaluate soil stratigraphy and erosion parameters. For this reason the USACE partnered with the U.S. Department of Agriculture, Agricultural Research Service (ARS), the U.S. Geological Survey (USGS), and Texas A&M University (TAMU) to improve the understanding of the uncertainty (aleatory and epistemic) associated with the erosion parameters and soil stratigraphy. The aleatory uncertainty is derived from natural variability in the soils, which is irreducible. Epistemic uncertainty, however, comes from limitations in the data collection, testing methods, and parameter estimation, which can be reduced through calibration. Several sites were identified along the LAR that had observed bank erosion information which could serve as useful calibration candidates.

BSTEM, developed by ARS, was chosen to assess the bank erosion potential because it incorporates both fluvial erosion and mass wasting processes (Simon et al. 2011, Klavon et al. 2017). Initially deterministic estimates of the expected bank retreat were conducted at sites where bank erosion was observed to occur. Since BSTEM models both erosion initiation and progression, calibration of the input parameters to observed erosion is possible.

BSTEM models discrete locations assuming up to five continuous and homogenous soil layers. As a result, the values used in BSTEM should be representative of how the entire soil layer performs through the modeling process, which may differ from specific measured values at a single point. Therefore, careful selection and calibration to observed erosion performance is essential to accurately model bank retreat using BSTEM. The gathered soil information was used to generate the stratigraphy for the BSTEM models and also the initial soil parameter values, parameter ranges, and distribution functions for use in both the deterministic and stochastic versions of the model. The derivation of the BSTEM soil stratigraphy also utilized information from existing boreholes on the American and Sacramento rivers as well as a three-dimensional stratigraphic model that was developed for a portion of the American River.

The calibration process developed for the American and Sacramento river sites utilized a multi-step process that included a correction of one-dimensional (1D) site hydraulics to account for non-1D flow phenomena, such as split flows or movement around a bend, utilization of representative geotechnical parameters, selection of the critical shear stress and erodibility coefficients based on observed soil type range, selection of an effective Manning's n value based on site vegetation following a vegetal cover factor approach (NRCS 2007), iterative adjustment of critical shear and erodibility coefficient within tested ranges of values by soil type, iterative adjustment of the effective Manning's n value to match the observed erosion bank retreat, and finally adjustment of geotechnical parameters to match the bank shape profile. The vegetal cover factor approach (NRCS 2007) defines a multiplying factor that tempers the normal shear stress acting at the site. With a cover factor of zero (no vegetation) the effective Manning's n value = 0.03. A cover factor of one would have so much vegetation that the effective Manning's n value is >0.3. The square of the ratio of the soil grain roughness to the effective Manning's n value is used along with the flow depth to modify the shear stress to obtain an effective shear stress directly acting on the soil particles in BSTEM. For additional information on the calibration and validation process please see Rivas 2020.

The initial set of BSTEM models was used to help calibrate model parameters to provide a more accurate representation of known lateral erosion rates and bank topography post bank retreat. Calibration at these sites resulted in the selection of erosion parameters by soil type for use at other locations where observed bank erosion data were not readily available. Figure shows a comparison of the calibrated values to those measured. Because the process of calibrating known parameters helps to minimize the epistemic uncertainty inherent in the data, the calibrated soil parameters were used to carry forward information gleaned about soil parameters during calibration and validation into design evaluations of bank erosion around Sacramento.

To evaluate the erosion risk throughout the Lower American River, additional BSTEM simulations were evaluated using hydraulics from a design event. The design hydrology was developed based on the desired levee capacity and potential increased spill capacity of the upstream Folsom Dam. BSTEM was then used with this design event to provide an estimate of the bank erosion risk at this higher, and as of yet, untested discharge.

To evaluate the aleatory uncertainty of soil properties, BSTEM was modified by ARS to allow users to input probability distributions of soil properties for Monte-Carlo simulations. Multiple combinations of model inputs are generated, each one being a single realization, and combined to provide a probabilistic bank retreat estimate based on the distribution of the input parameters. Unlike the input parameters for the deterministic BSTEM modeling, the stochastic model requires a description of the parameter distribution. This parameter distribution was initially based on the theoretical distribution that best fit the tested soil parameters. This was a gamma distribution for both the critical shear stress and the erodibility coefficient parameters.

The initial thought was that the 50% bank retreat probability estimate from the stochastic runs should be around the calibrated deterministic value since these were the values used to help define the central tendency of the fitted distribution. When the stochastic BSTEM model was employed at the calibration sites, however, most sites indicated the deterministic bank retreat was around the 25% bank retreat probability estimate. An example of this initial stochastic BSTEM model results is shown in Figure 3.

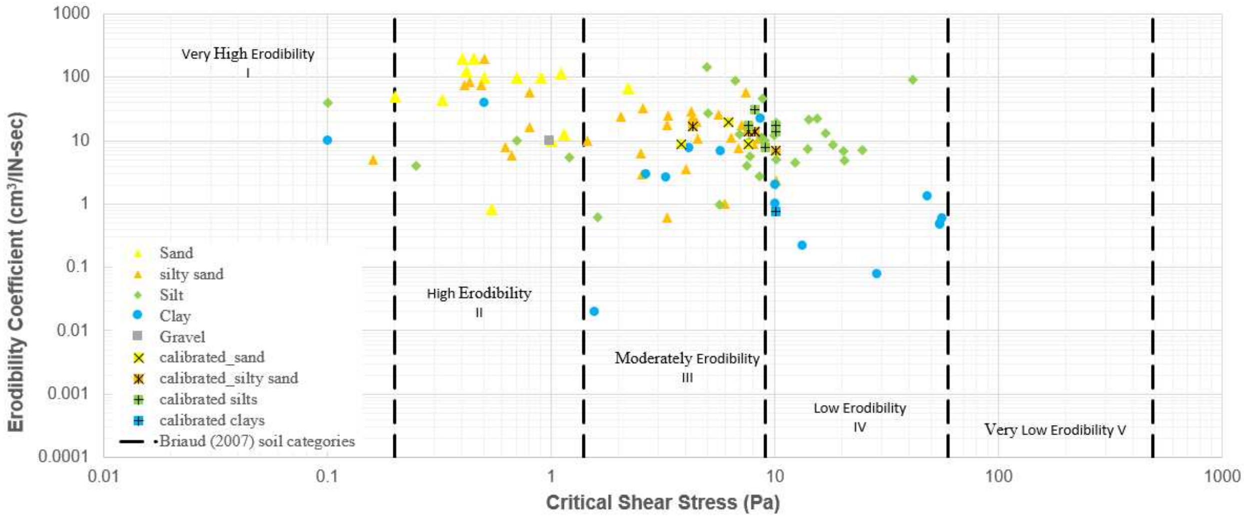

Figure 2. Collected erosion parameters on the American and Sacramento Rivers by soil type compared with soil erosion categories identified by Briaud (2013) and calibrated values from sites with observed bank erosion.

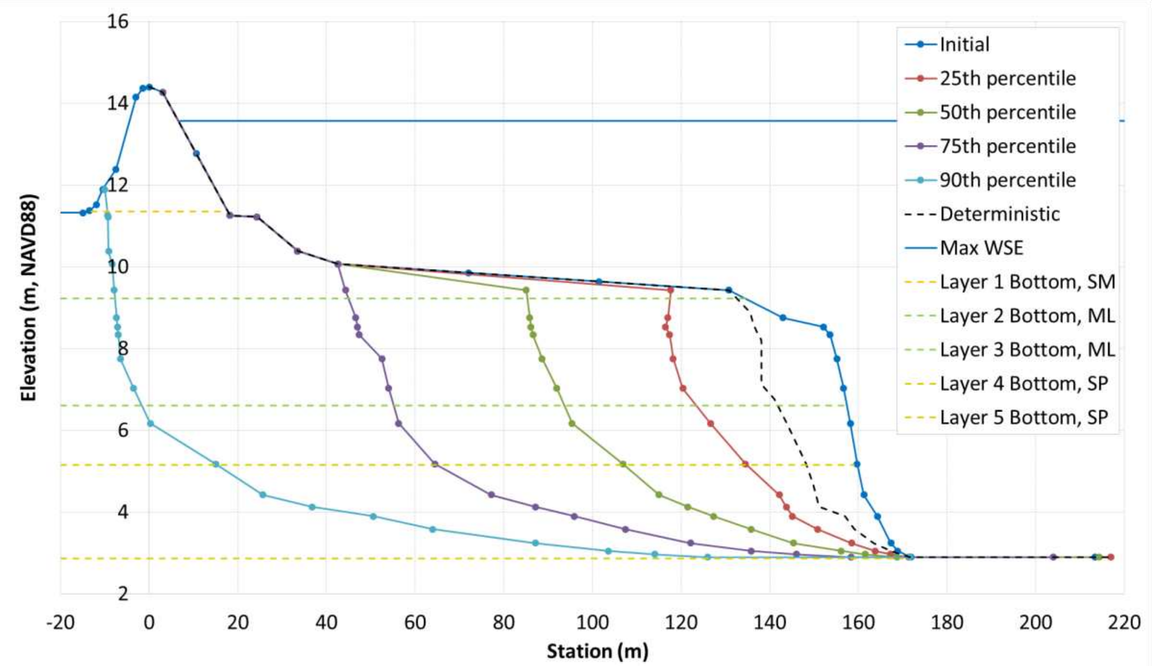

Figure 3. Modeling site LAR 8b: comparison of the simulated deterministic bank retreat with simulated stochastic non-exceedance percentiles for lateral bank retreat using gamma distributions of bank-material properties based on setting calibrated value to the mode of the distribution. Shown is the design scenario with uniform effective Manning *n* set at the deterministic calibration values.

In the exploration of this discrepancy, it was observed that the minimum and maximum ranges used to define the initial stochastic range cut off a portion of the distribution (creating a skew towards more erosive conditions). It was also discovered that the manner in which the gamma distributions were being determined also created a skew towards more erosive conditions. The gamma distributions were defined based on the site calibrated parameter (critical shear stress and erodibility coefficient) to help carry forward the reduction in epistemic uncertainty realized during calibration of the bank retreat. The calibrated values were set equal to the gamma distribution mode (an explicit solution to the median of the gamma distribution is not available). The resultant distributions, however, tended to create stochastic scenarios where the 50% value (median) of the cumulative distribution function (CDF) was greater than the calibrated value. Because the triangular distribution has an explicit solution for the median value, this distribution was chosen to evaluate how well aligning the calibrated deterministic value with the median (50% of the CDF) value would perform. In essence, the peak of the triangular distribution was defined by setting the calibrated value to the distribution median and the distribution range to the observed range in the tested data. The maximum extent of the triangular distribution was defined within the observed range for all soil types, but adjusted by soil type to allow a better fit to the calibrated deterministic values. This in turn (see Figure 4) provided a correlation between the deterministic and stochastic simulations that was in line with the original expectation and enabled the reduction in epistemic uncertainty in the deterministic models to be carried forward into the stochastic evaluation of bank erosion, increasing the confidence of the bank erosion distributions. It was also felt to be a better representation of the natural aleatory uncertainty that exists with bank erosion because of the heterogeneity and anisotropic nature of fluvial sediment deposition.

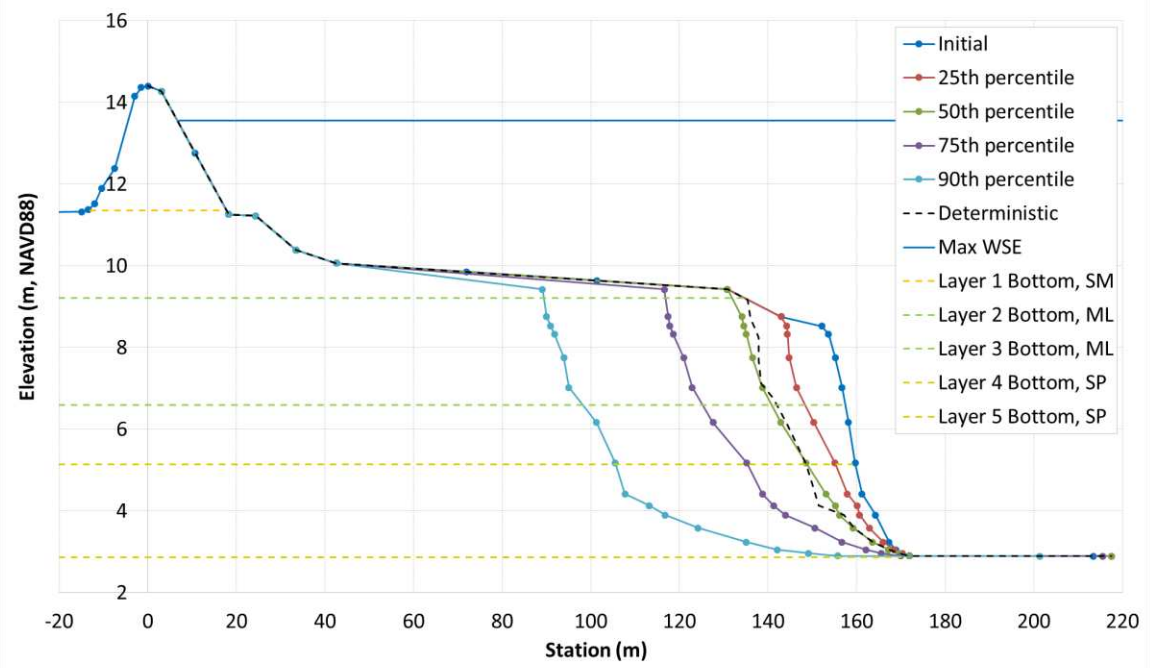

Figure 4. Modeling site LAR 8b: comparison of the simulated deterministic bank retreat with simulated stochastic non-exceedance percentiles for lateral bank retreat using triangular distributions. Shown is the design scenario with uniform effective Manning's n set at the deterministic calibration values.

Evaluation of reaches along the Lower American River using the updated stochastic distributions were conducted within BSTEM for the design scenarios to evaluate the likelihood of bank erosion reaching the levee in a single design event. Five hundred random sets of BSTEM parameters were generated through the defined stochastic distributions to simulate potential bank erosion for each set of parameters. The resulting percentiles, as shown in Figure 4, indicate the percent of simulations that had less erosion. The eroded bank top estimated by BSTEM can be plotted spatially with the known location of the levee to assess bank erosion risk and inform erosion countermeasure site selection and design on the American River.

CONCLUSION

BSTEM simplifies the complexity of the erosion processes and includes both fluvial erosion and slope stability failures. BSTEM is a substantial advancement beyond other available methods that only consider erosion initiation or rely on a single deterministic result from the excess shear equation, and do not consider slope failures. Reliability of the results is significantly improved beyond what can be expected from using published values by calibrating the model to observed site-specific conditions. The probabilistic estimates, once adjusted to match the reduced epistemic uncertainty achieved in the deterministic calibration process, allow the user to quantify the erosion estimate uncertainty for design events not yet experienced around Sacramento. The resulting BSTEM outputs incorporate the measured intrinsic erosion and geotechnical properties of the soil and reduced epistemic uncertainty from calibration. This provides the ability to assess sections of levees around Sacramento that are most prone to erosion risk at design events close to the levee capacity and help make better risk informed decisions.

To produce quality results from BSTEM requires quality inputs to the model. Soil sampling and testing discussed in part 1, along with the data processing that incorporates calibration and validation discussed in this paper (part 2), were achieved through the collaboration of USACE, USGS, ARS, and TAMU. These combined efforts were critical for achieving quality erosion estimates from BSTEM for use in risk-informed erosion countermeasure site-selection and design to reduce flood damage risk to Sacramento.

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