SCOUR CHARACTERIZATION DUE TO WATER FREE FALL

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ABSTRACT

Characterization of scour due to free fall of water during storm surge is important for transportation related structures. The roads and streets behind levees are the most typical structures, which are vulnerable to storm surge. A sustained storm surge overtopping a floodwall or weir can cause scour of landside embankment soils, which can compromise embankment stability. Presence of wave action also contributes to scour progression and loss of lateral support. As lateral support is reduced, the overloaded retaining structure can start tilting and exacerbating the instability. Scour depth and stresses due to vertical flow are dependent on shear stresses induced by the plunging water or vertical jet, height of the wall, storm surge and wave heights, depth of the plunge pool on the landside of the retaining structure or a floodwall, and erosion rate of the levee soils. This paper focuses on estimating scour depth and hydraulic stresses imposed by overtopping due to a sustained storm surge. The analysis results are compared to observed scour depths on the landside of floodwalls after Hurricane Katrina along the Inner Harbor Navigation Channel (IHNC). The findings show that for transportation structures which are prone to water free fall during storms, it is important to consider impinging effect of water on soil supporting transportation structures.

Keywords: soil erosion, floodwall overtopping, scour, levee

INTRODUCTION

Free fall of water on highway embankments or roads causes scour and introduces instability. The impingement of water on the soil surface may also happen in elevated culverts outlets. The scour created by the free fall water can be different than the scour created around the bridge piers. The current design practice does not distinguish between the scour developed by water free fall and scour developed by passage of water parallel to soil surface. The objective of this paper is to demonstrate that the water flow parallel to soil surface and water free fall can result in very different scour depth. In order to characterize the scour generated by water free fall, overtopping of floodwalls are selected, because the scour monitoring data associated with levees are readily accessible.

Floodwalls are overtopped when flood levels reach the floodwall top elevation. Consequently, a free jet is formed and impingement of this free jet on the landside causes erosion and loss of floodwall lateral support as is shown in Figure 1. Once the shear stresses exceed the shear strength of the levee material, erosion occurs. The imposed shear stresses on the levee material are greater than for normal levee overtopping because of the vertical drop. The induced shear stresses have been estimated by many researchers (*1; 2; 3; and 4*). In this study, a scour analysis is conducted using the excess shear stress approach developed by Hanson et al. (2002).

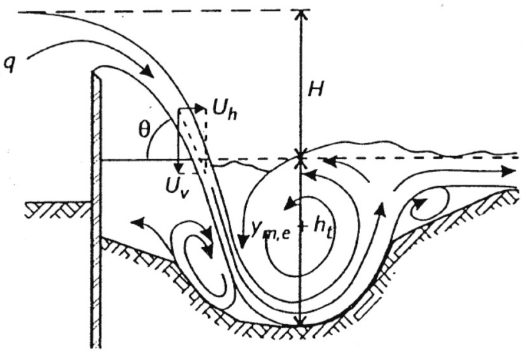

FIGURE 1 Scour hole formation by overtopping jet (*5*).

THEORETICAL FRAMEWORK

Applied Shear Stresses

Still, i.e., no waves, water overtopping a floodwall can be approximated by flow over a sharp-crested weir. The discharge of flow for this problem can be calculated using Equation 1 (*6*):

$$\begin{aligned} q &= C_d \frac{2}{3}\sqrt{2g}\,h_1^{3/2} \\ C_d &= 0.611 + 0.08\left(h_1 / h\right) \end{aligned} \tag{1}$$

where, C_d, is discharge coefficient; h_1 is height of the surge above the wall; and h is depth of the water as shown in Figure 2. Using the discharge and surge height, the upstream velocity (V_1) of flow over the weir from the floodside can be determined and is important for assessing the erodibility of the landside soil (see Figure 2).

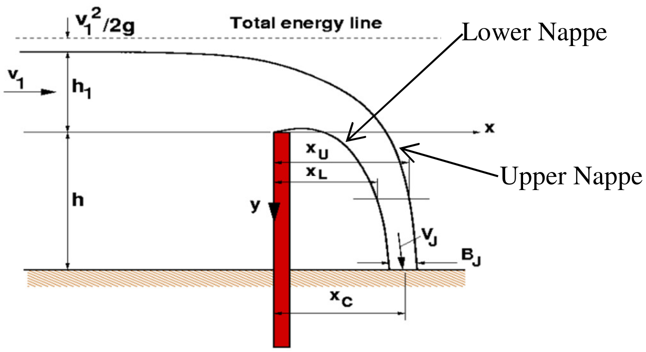

FIGURE 2 Flow over a sharp-crested weir (modified after USACE 2011).

The jet profile overtopping the floodwall has two surfaces which are called lower and upper nappes (nappe is a French word meaning "a continuous surface") as shown in Figure 2. The trajectories of the lower and upper nappes are calculated based on open channel hydraulics (*7; and 8*). The profile of nappes at the impingement point of nappe to soil is determined based on surge height and velocity of the flow at the upstream. Consequently, the width of trajectory (B_J), velocity of the flow (V_J), the jet entry angle and its centerline distance from the wall (X_C) can be estimated at the impingement level (*6*). This jet can start eroding the landside surface material and develop a scour trench as shown in Figure 3 along the Inner Harbor Navigational Channel (IHNC) during Hurricane Katrina. In this case a surge crest of 0.6 m to 0.75 m above the floodwall, and probably some wave overtopping of 0.3 to 0.6 m, impacted the landside earthen levee causing the scour trench in Figure 3.

FIGURE 3 Scour and erosion trench on landside of IHNC during Hurricane Katrina. (*9*).

In cases where an overtopping jet enters a landslide plunge pool, it diffuses in the water (see Figure 4). The centerline velocity of the jet remains constant for a distance of approximately six times the entry jet thickness. This distance has been referred to as the potential core length, J_p (*10*). Beyond this distance, the velocity (U) decreases as the jet diffuses and is defined using Equation 2 (*1 and 3*):

$$\frac{U}{U_0} = C_d\sqrt{\frac{y_0}{J}} \qquad \text{where} \qquad J > J_P \tag{2}$$

where J is the distance along the jet centerline from the nozzle origin to the eroding bed, C_d, diffusion constant which is assumed to be 2.6 in this study (*3*).

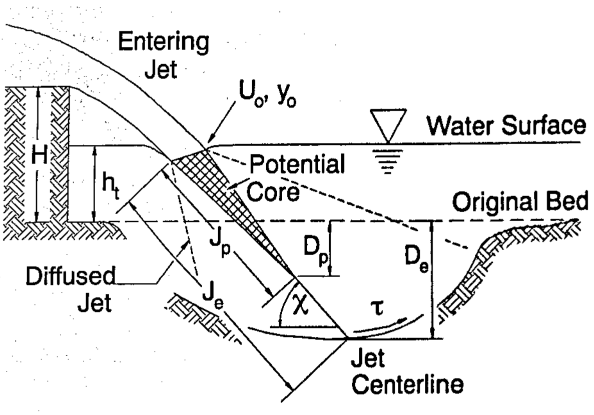

FIGURE 4 Schematic of free overfall scour setup and parameter definitions (*11*).

The maximum shear stresses acting upon the ground are a function of maximum velocity (U) in the impingement region (*3*) and is calculated using Equation 3:

$$\begin{aligned} &\tau_0 = C_f \rho U_0^2 \qquad \text{where} \qquad J \le J_P \\ &\tau = C_f \rho \frac{y_0}{J}(C_d U_0)^2 \qquad \text{where} \qquad J > J_P \end{aligned} \tag{3}$$

where J is the distance along the jet centerline from the point of pool entry to the eroding bed; J_P is length of the jet potential core; U_0 and y_0 are jet velocity and jet thickness as it enters the pool; C_d is diffusion coefficient; and C_f is friction coefficient which is a function of Reynolds number.

Soil Erosion

The erodibility of soil is defined as the relationship between erosion rate and the velocity of water flowing over it or shear stresses developed by the water at the water/soil interface (*12*). In practice, the scour analyses are commonly conducted using the erosion function charts. These charts are produced using Erosion Function Apparatus (EFA) test (*12; and 13*). The EFA test was primarily developed to simulate erosion around bridge piers. Therefore, in this test water flows over a horizontal surface of soil sample and the erosion rate is monitored.

Govindasamy (2009) reports erosion rates obtained from EFA tests on low and high plasticity clays (i.e., CL and CH) which are shown in Figure 5 and Figure 6, respectively. These figures were modified herein to demonstrate the average, lower, and upper boundaries for the CL and CH materials tested. These boundaries are used to estimate the erosion rate for the stresses imposed by an overtopping water jet.

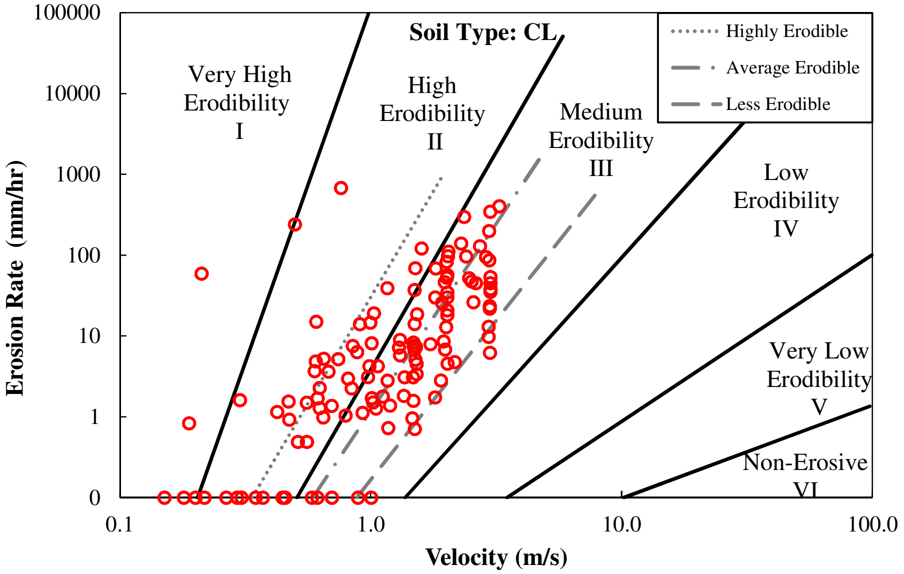

FIGURE 5 EFA test data for low plasticity clays (CL) plotted on the Erosion Function Chart (modified after Govindasamy, 2009 (*13*)).

The scour depth is a function of erosion rate and shear stress. The shear stress is a function of depth of scour and plunge pool depth. Therefore, the scour depth due to surge height above the floodwall is determined through an iterative procedure, which is summarized below:

- The velocity and width of overtopping jet at soil impingement level is estimated for the selected time step. If the water is plunged on the landside, the velocity and width of overtopping jet at plunge pool surface must be calculated.
- The depth of scour is assumed zero at the selected time step.
- The potential core length is determined.
- The shear stress induced by the jet is calculated using Eqs. 2 and 3.
- The erosion rate is calculated for the shear stress induced using the average, lower, and upper boundary lines shown in Figure 5 and Figure 6.
- The scour depth is calculated for the selected time step.
- If the scour depth is different than what was assumed, this procedure is repeated until agreement is obtained between the assumed and calculated depths.

The effect of wave overtopping on scour depth is also important and may be more important than storm surge height. The trajectory of the wave overtopping is a function of wave height, wave period, and surge elevation relative to the wall. The hydrodynamic nature of the wave overtopping is complex and the subject of a future paper.

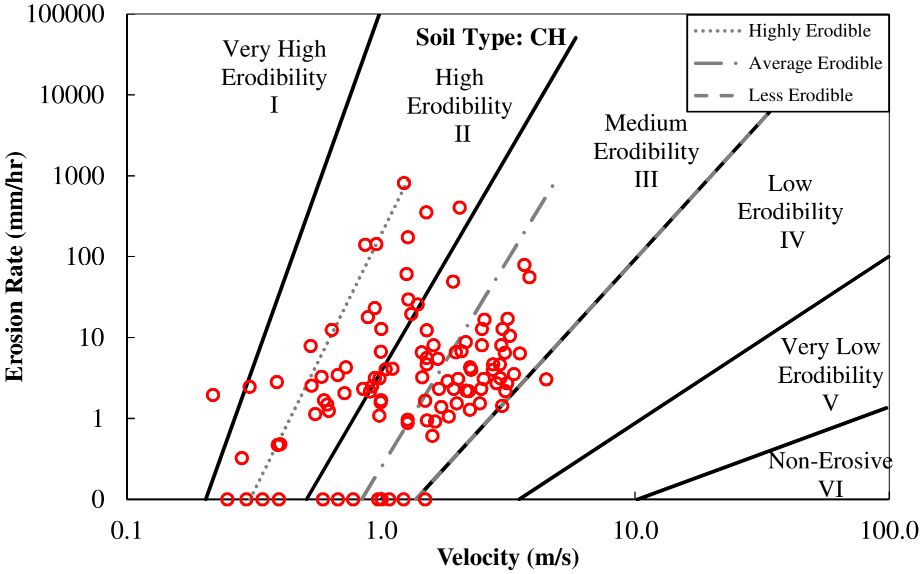

FIGURE 6 EFA test data on high plasticity clays (CH) plotted on the Erosion Function Chart (modified after Govindasamy, 2009 (*13*)).

SCOUR DEPTH ANALYSES

In order to demonstrate the influence of water free fall, the scour monitoring data of floodwalls in New Orleans are used herein. The floodwall overtopping during Hurricane Katrina resulted in scour trenches behind many floodwalls throughout New Orleans (see Figure 3). Along the IHNC the levee soil consists of low to high plasticity clays at different stations (*9*). The hydrographs reported for the flood and landsides of floodwall along the IHNC during the Katrina are shown in Figure 7.

After Hurricane Katrina, Independent Levee Investigation Team (ILIT) conducted EFA tests on soil samples collected from eleven locations that were likely overtopped during Katrina in New Orleans (*14*). Figure 8 shows the test results for twenty-four samples. This graph shows the majority of the clayey samples exhibit medium erodibility. The sandy samples show high to very high erodibility. Although there was no sample tested from the IHNC levees, the erodibility of clayey levees in IHNC is assumed within the range of other locations in New Orleans. A comparison between Figures 8 and Figures 5 or 6 shows that the average erodibility boundary lines for CL and CH materials shown in Figures 5 and 6 are a reasonable representation of the erodibility of clayey samples collected from New Orleans's levees.

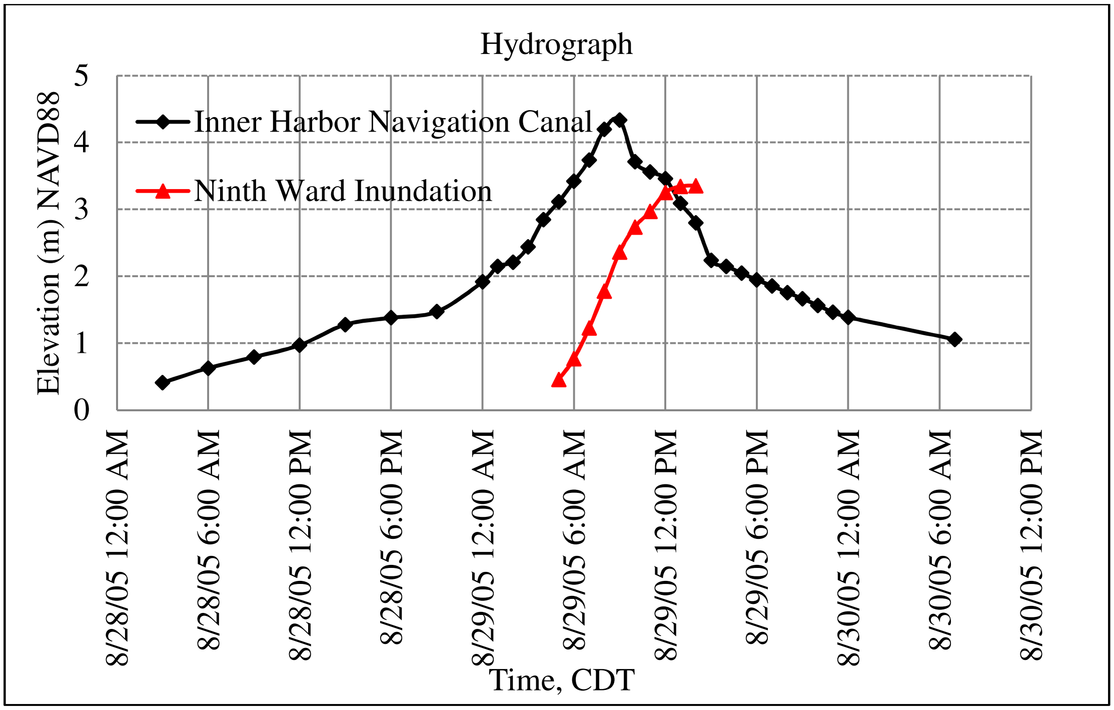

FIGURE 7 Hydrographs for water levels on flood and landsides along the IHNC.

The scour analyses were conducted using wall top elevations of 3.20 m (10.5 ft), 3.51 (11.5), 3.73 (12.25), 4.04 (13.25), and 4.27 (14.0) m (ft) NAVD88 [2004.65] for levees with low and high plasticity clayey soils. The exposed wall height was assumed to be 2.13 m (7 ft) representing the exposed wall height of most of the IHNC just west of the Lower Ninth Ward. The analysis results are shown in Figure 9 and show the scour depth for a highly erodible CL and a wall top elevation of 3.73 m (12.25 ft) NAVD88, is about 1.75 m. This scour depth can be used to determine whether or not it will undermine the floodwall and whether a concrete apron should be installed on the landside to resist surge scour.

Some studies of the levees along the IHNC just west of the Lower Ninth Ward estimate the exposed height of the flood wall was only about 1.8 m (6 ft) at the time of Hurricane Katrina. As a result, the scour analyses were also conducted using a wall height of 1.8 m (6 ft). The estimated scour depths for these analyses are within 6 to 7 percent of estimated scours based on exposed wall height of 2.13 m (7ft).

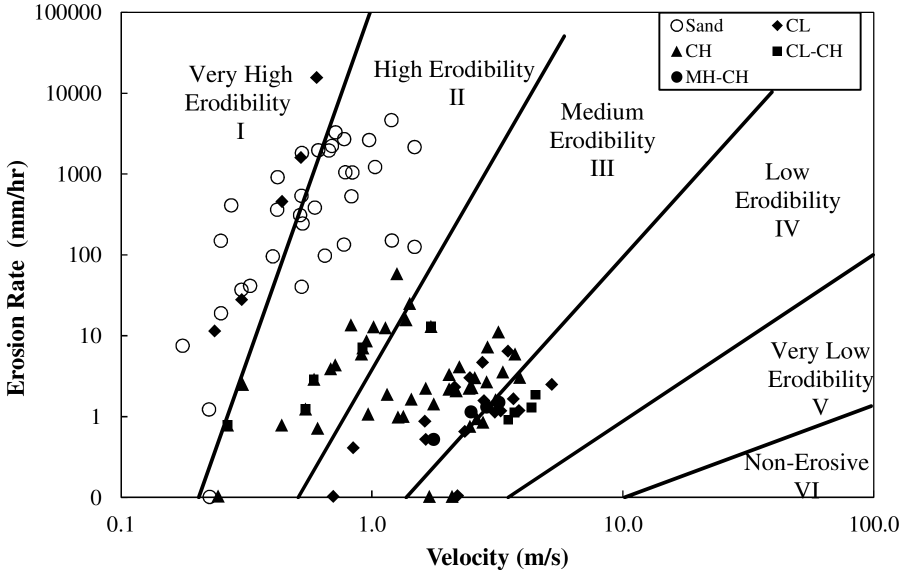

FIGURE 8 EFA test results for 24 levee samples (modified after ILIT 2006 (*14*)).

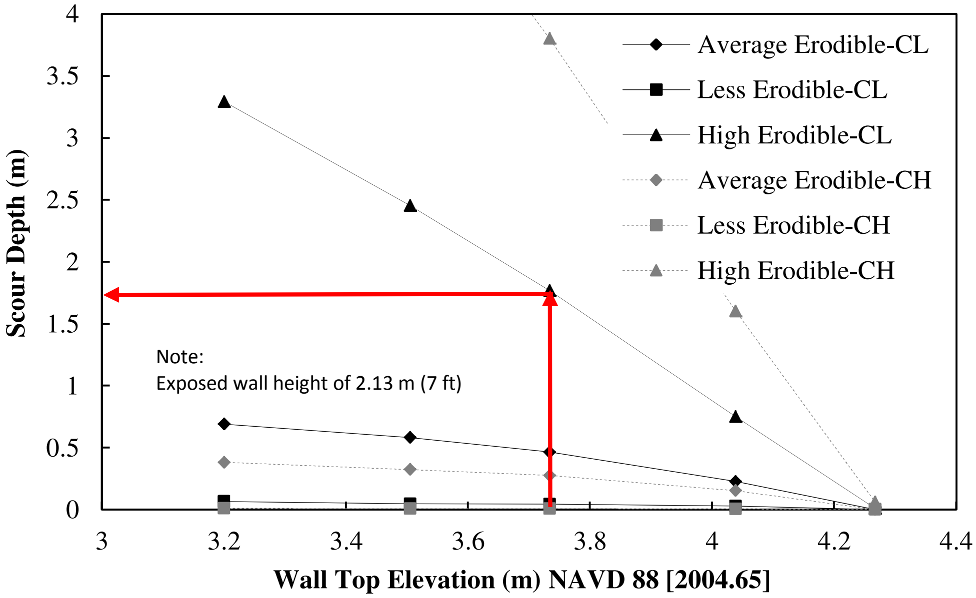

FIGURE 9 Scour depth analysis results for low and high plasticity clayey soils.

COMPARISON WITH FIELD OBSERVATIONS

The analysis results show that scour depths for the IHNC floodwall along the Lower Ninth Ward with top elevation of 3.81 m (12.5ft) NAVD88 should be about 0.43 and 0.25 m (1.4 and 0.82 ft) on average for CL and CH levee soils, respectively, from Figure 9. These estimated scour depths do not consider wave action. More importantly, the presented scour predictions are based on erosion rates obtained from Erosion Function Apparatus charts which may not represent the erosion rates due to the nearly vertical overtopping jets instead of flow around bridge piers. Some studies on the performance of levees along the Lower Ninth Ward suggest a top elevation of the floodwall of 3.2 m (10.5 ft) NAVD88. The analyses results for this wall top elevation show scour depths of 0.69 and 0.38 m can develop for the CL and CH levee soils, respectively, from Figure 9. The measured scour depth along the IHNC are about 0.6 m to 1.2 m (2 ft to 4 ft) deep and significantly greater than the estimated values in this study which provides how the commonly used methodology can underestimate the scour depth due to neglecting the importance of water free fall and wave action effects.

The estimated horizontal distance of overtopped jet impingement to the ground surface or plunge pool is estimated to be up to 1.6 m (5.3 ft) and 2.1 m (6.9 ft) from the floodwall for top of wall elevations of 3.81 m (12.5 ft) and 3.2 m (10.5 ft) NAVD88, respectively. The width of the water jet at the entry to the plunged pool is estimated to be 0.17 m (0.6 ft) and 0.51 m (1.7 ft) for the wall top elevations of 3.81 m (12.5 ft) and 3.2 m (10.5 ft) NAVD88, respectively. The measured scour trench widths along the IHNC floodwalls were about 1.5 m to 2.1 m (5 ft to 7 ft). As a result, the analysis presented herein also underestimates the width of the water jet probably.

In summary, the existing analysis of a vertical water jet plunging over a sharp-crested weir does not appear suitable for water free fall analyses. As a result, the scour depth and scour trench width are underestimated because the commonly used method approximates the erosion characteristics of the soil using the EFA test which simulates horizontal flow around bridge piers instead of vertical flow over a floodwall. Also, wave overtopping is likely in high wind events, which is not accounted in the design. This analysis may be suitable for flood events caused by excessive upstream precipitation which create a slow rise in the retained water and limited wave. An example of such an event is the 2011 Mississippi River flood (*15*) which washed out many roads.

CONCLUSIONS

The analyses presented herein show scour characterization analyses can be performed using the iterative procedure outlined herein for events with a sustained flood level. The presented methodology also can be used when there is a plunging pool. However, this methodology will not accurately estimate observed scour depths if wave overtopping occurs for the following two reasons. First, wave action is expected to introduce higher jet velocities when it impinges the ground. Second, the shear stresses acting upon the ground due to overtopping jets over floodwalls are greater than the shear stresses induced by nearly horizontal flow used in the Erosion Function apparatus. Therefore, the current design methodology for scour potential analyses of road embankments where elevated grounds are located adjacent to the roadway or free fall of water at the outlet of culverts should be used cautiously with considering its limitations.

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