Responses of sandy seabed under combined waves and current: Turbulent boundary layer and pore-water pressure

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ABSTRACT: Numerous offshore structures have been constructed in severe ocean environments where waves are usually coexisting with current. Previous studies on the seabed response mainly focused on either wave induced pore-pressure in the soil or the particle-transport of surficial sediments, etc. In this study, the sandy seabed responses in combined waves and current were physically modelled with a specially-designed water flume. The flow velocities in the boundary layer and the pore-water pressure in the sand-bed were simultaneously measured with an Acoustic Doppler Current Profiler (ADCP) and miniature Pore Pressure Transducers (PPTs) respectively. In the physical modelling of wave-current coexistence, both the following-current and opposing-current were superimposed on the travelling waves respectively. Experimental results indicate that the pore-pressure amplitudes are enlarged for the following-current case and reduced for the opposing-current case. This coupling effect is more obvious for the waves with shorter periods. The wave-induced seepage has slight effect on velocity profiles in the boundary layer for the examined hydrodynamic loads and the medium sands.

1 INTRODUCTION

With the ocean current and waves travelling along the seabed, the pore pressure may be generated in the soil. Numerous investigations of the wave-induced pore pressure response of the seabed under wave loading have been performed. The pressure response of the seabed is significantly different when a current is superimposed onto waves compared with that without a current. Until now, the experimental observation on the seabed response in combined waves and current is quite scarce. Therefore it is of interest to examine the dynamic process around the water-soil interface under the action of combined waves and current.

Existing experimental observations have showed that the wave-induced upward seepage exerts lifting forces onto the sand grains under the wave-troughs and thereby brings the sand more susceptible to scour (see Qi et al. 2012). The upward seepage may decrease the turbulence intensity of the boundary layer, therefore reduce the bed shear stress and go against the incipient motion of the sand grains. The final outcome depends on the relative magnitude of the aforementioned two opposing effects (Nielsen et al. 2001).

Many studies had been performed on the effects of the pore pressure gradient on sediment grains incipient motion. Some conflicting results were provided on whether the seepage affects sediment motion (Lu et al. 2008). Martin (1970) observed that the seepage out of the bed did not affect incipient motion significantly because the seepage force is lost once a sediment particle rocks. Carstens et al. (1976) considered that the insensitivity of the incipient motion to vertical pressure gradients is applicative to any combination of steady or oscillatory flow and pressure gradient. Baldock & Holmes's (1998) experiment indicated that the incipient motion of the sediment is little affected by vertical pressure gradients and no appreciable motion occurred until the critical gradient for liquefaction was neared. The aforementioned studies put forward their conclusions mostly based on some topographical observations in the experiment, and mainly focused on the current-only condition while waves and current generally coexist in real ocean environments.

It has been proved that the seepage can modify the velocity distribution of open-channel flows significantly (Lu et al. 2009, Chen & Chiew 2004). However, the effect of wave-induced seepage on the velocity distribution of waves plus current flow has not been well understood yet (Liu et al. 1996).

In the present study, a series of large flume tests were conducted, the velocity profile of the boundary layer was measured and analyzed under both waves-only condition and waves plus current condition, which may provide an explanation about the effect of the pressure gradients on the sediment incipient motion.

2 EXPERIMENTAL INVESTIGATION

2.1 *Experimental set-up*

The experiments were conducted in a flow-structure-soil interaction flume (52 m long, 1 m wide and 1.5 m high) at the Institute of mechanics, Chinese Academy of Sciences. This specially-designed flume is capable of synchronously generating waves and current. A specially designed large soil-box (6.0 m in length, 1.8 m in depth and 1.0 m in width) is located in the middle section of the flume, and a segment of 2.0 m × 0.5 m × 1.0 m (length × depth × width) was employed in this series of experiments. The water depth (h) was kept constant at 0.5 m, as illustrated in Figure 1.

A saturated sand-bed was adopted to simulate a sandy seabed, whose main physical properties are listed in Table 1.

The arrangement of the PPTs is detailed in Figure 1. Four GE Druck miniature PPTs were utilized to measure the wave-induced pore water pressure in the soil. Two Wave Height Gauges (WHG) were located just above the PPTs. Far-field wave height was measured with the other two WHGs to guarantee the accuracy and reliability of the measured wave height and calculated wave length. The signals of WHGs and PPTs were multichannel synchronous sampled via the NI USB-6255 Data Acquisition Card. An ADCP was mounted to measure the flow velocity at the level of 0.5 h (0.25 m) above the sand-bed near the PPTs. In the experiment to measure the velocity profile of the boundary layer, the height of the ADCP
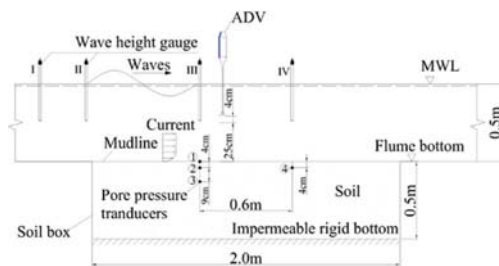

Figure 1. Schematic diagram of the experimental system.

Table 1. Index properties of test sands.

Mean size of sand grains, d_{50} (mm)	Coefficient of permeability, k_s (m/s)	Void ratio, e	Relative density, D_r	Buoyant unit weight of soil, γ' (kN/m³)
0.38	1.88×10^{-4}	0.771	0.352	9.03

installation was adjusted to cover the boundary layer close to the seabed surface.

Two series of experiments were carried out: (I) pore pressure response experiments; and (II) velocity profile of the boundary layer.

In the experiment (I), to study the effect of the magnitude and flow direction of the current velocity on the seabed response, a series of magnitudes of following-current and opposing-current were employed. Moreover, a series of waves with various values of wave heights and a fixed value of wave period ($T = 1.2$ s) were adopted to study the effect of the wave height on the seabed response, and another series of waves with different wave periods and a fixed wave height ($H = 9.5$ cm) were employed to study the effect of the wave period on the seabed response.

In the experiment (II), the test duration was chosen to be more than 600 s based on extimates of the wave and turbulence time-scales (Klopman 1994).

2.2 *Testing procedure*

In general, the testing procedure was adopted as follows:

1. The flume including the soil box was firstly emptied and cleaned.
2. The PPTs were deaired and then saturated to ensure their argil-covers being free of air. They were then installed at the specific locations with the support of a rack (see Fig. 1);
3. The soil box was whereafter filled with clean water to a certain depth. The sand bed was carefully prepared by means of sand-raining technique. The surface of the sand bed was leveled off smoothly with a scraper.
4. The flume was then filled slowly with water to a given depth (e.g. 0.5 m).
5. Both the wave maker and the current generator were switched on to generate waves and current concurrently.
6. The multichannel synchronous sampling system was then started to measure the multi-physics parameters in the aforementioned two series of experiments, e.g. wave height, pore pressure and flow velocity.

3 RESULTS AND DISCUSSION

3.1 *Effects of imposing a current upon waves on pore pressure response*

One main objective of the study is to investigate the effect of current on the wave-induced seabed pore pressure response. Two aspects of parameters including the magnitude of the current velocity and

the wave characteristics were examined in detail. The other is to examine the influence of wave-induced seepage on the velocity profile of the boundary layer under combined waves and current.

3.2 *Effect of the magnitude of the current velocity*

Figure 2 (a) and Figure 2 (b) give a time series of wave profiles and pore pressure response at the same measuring section of the flume under waves-only condition and waves with following-current condition separately. It is indicated that both the wave profile and regular wave-induced instantaneous pore pressure present a sinusoidal variation. No pore pressure accumulation is found for the examined hydrodynamic loads and the medium sand due to the large grain diameter ($d_{50} = 0.38$ mm) and a high permeability of the soil ($k_s = 1.84 \times 10^{-4}$ m/s) in the tests. Pressure exerted on the seabed and the variations of wave profiles are
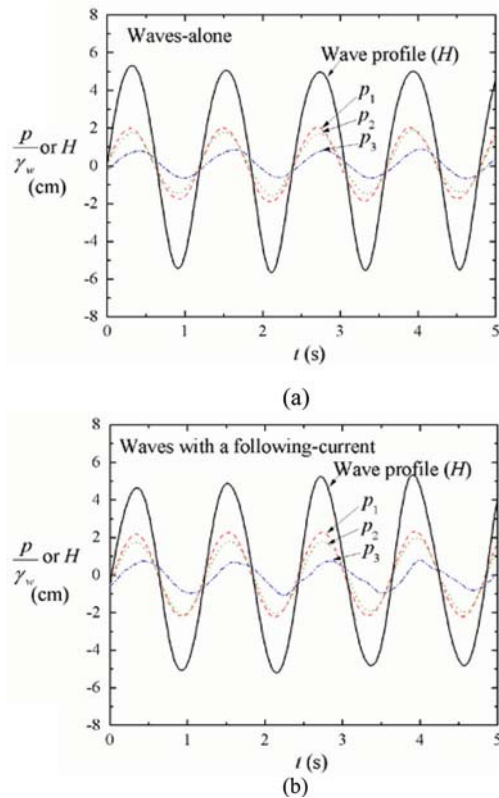

(a)

(b)

Figure 2.   Wave profiles measured with WHG-III and pore pressure measured with PPT1 (p_1), PPT2 (p_2) and PPT3 (p_3): (a) waves-alone condition and (b) waves with following-current condition. (Waves: T = 1.2 s, H = 10.2 cm; current: U_c = 0.23 m/s).

in-phase. A phase lag is evidently shown by comparing three time series of pore pressure response (p_1, p_2 and p_3) measured at different seabed depths at the same section. Comparison between Figure 2 (a) and 2 (b) indicates that with the fixed wave parameters, superimposing a following-current onto waves barely has effect on the phase lag of the seabed response.

Figure 3 shows the velocities variation with time under different loading conditions measured at the level of 3 mm above the bed. It is clearly indicated that imposing a current increases the turbulence of the flow significantly.

While waves and current coexist, the presence of the current will change the original wave height and wave length because of the interactions between waves and current. Figure 4 shows the variation of the wave height (H) and wave length (L) with the velocity of the current component (U_c). A theoretical variation of wave height and wave length with current velocity based on the linear theory of wave-current interaction is also given in Figure 4, which is calculated with (see Zou 2004).

$$H/H_0 = 2\left[1 + 4U_c/c_0 + \left(1 + 4U_c/c_0\right)^{1/2}\right]^{-1/2}$$
$$\times \left[1 + \left(1 + 4U_c/c_0\right)^{1/2}\right]^{-1/2} \qquad (1)$$

and

$$L/L_0 = \left[1 + \left(1 + 4U_c/c_0\right)^{1/2}\right]^2 \Big/ 4 \qquad (2)$$

in which H_0 is the wave height without a current, $c_0 = L_0/T$ is the wave velocity without a current,
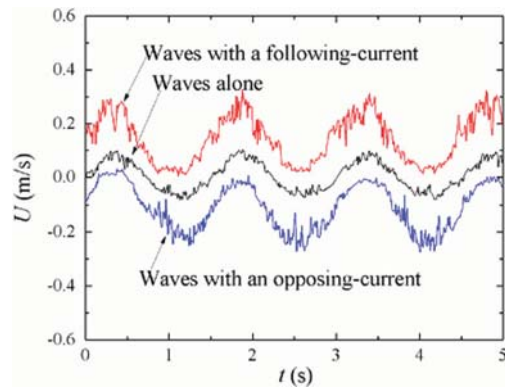

Figure 3.   Comparison of the flow velocities measured 3 mm above the seabed between the condition of waves alone, waves plus following-current and waves plus opposing-current. (Waves: H_0 = 7.2 cm, T = 1.5 s; current: U_c = 0.20 m/s & −0.20 m/s).
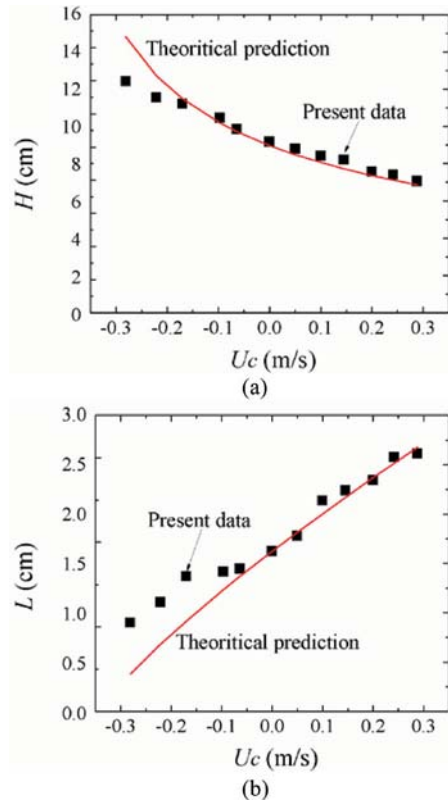
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Figure 4. Effect of the current on the: (a) wave height (H) and (b) wave length (L). (Waves: T = 1.2 s, H_0 = 10.2 cm).
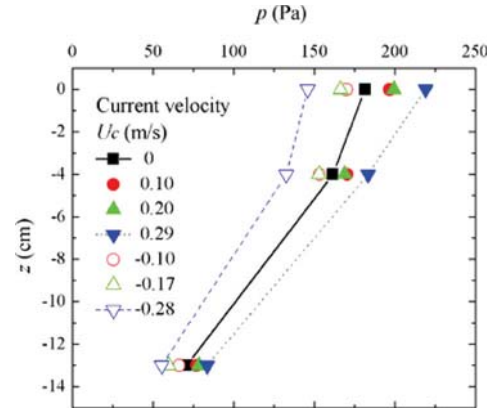

Figure 5. Comparisons of the vertical distributions of the wave-induced seabed response between the cases of waves-alone, waves with a following-current and waves with an opposing-current (T = 1.2 s, H_0 = 9.5 cm).
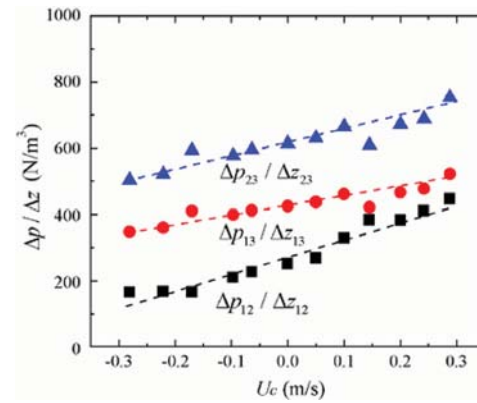

Figure 6. Effect of the current on the pore pressure gradient (T = 1.2 s, H_0 = 9.5 cm).

and L_0 is the wave length without a current. The experimental results and theoretical results are in good agreement in the current velocity range U_c > −0.1 m/s. The discrepancy between experimental results and theoretical results while U_c < −0.1 m/s is probably due to the nonlinear effect of the waves. It is seen that, H decreases and L increases significantly with increasing the value of U_c while a following-current exists, and H increases and L decreases with increasing the absolute value of U_c while an opposing-current exists.

Figure 5 illustrates the vertical distributions of the seabed response under different combinations of waves and currents loadings. It is indicated that if a following-current is superimposed onto waves, the amplitude of the seabed response is basically greater than without current, and vice versa. As the magnitude of the current velocity increases, the relative difference of the amplitude of the seabed response becomes greater. The maximum relative difference of the amplitude of the seabed response between the two conditions U_c = −0.28 m/s and

U_c = 0 m/s can be up to 20%. It is also observed that the relative differences of the amplitude of the seabed response under waves and following-current are basically equal to those under waves and opposing-current when the magnitude of the current is the same, e.g. U_c = −0.28 m/s and U_c = 0.29 m/s. The results indicate that the liquefaction or partial liquefaction is more likely to occur under combined waves and following-current loading, while the opposing-current is beneficial to prevent the seabed to liquefying. A following-current may be a potential risk for the safety of offshore structures.

As aforementioned, the wave-induced seepage has remarkable influence on the incipient motion of sand grains. As shown in Figure 6, the presence of a following-current makes the magnitudes of

the maximum pore pressure gradients within the measuring depth increase observably, while the opposing-current has the opposite effect. The relative difference of the pore pressure gradient caused by superimposing a following-current seems more remarkable in the upper seabed. Although the magnitudes of the difference of the gradients caused by the presence of the current is not large in the present experiment, the difference may become significant in a real ocean environment where the wave height and wave period can be more than 10 times greater than those in the flume experiment.

3.2.1 Effect of the wave characteristics

In this section, the effects of wave parameters on the seabed response will be investigated. Two wave parameters, wave height and wave period, are considered here.

As indicated in Figure 7, the seabed response under waves alone scales up as the wave height increases. The distribution profiles of the seabed response with relatively small wave heights are somehow different with those with bigger wave heights. The decreasing rate of the seabed response along with the soil depth reduces with the increasing depth for relatively small wave heights, while the rate increased for relatively bigger wave heights.

Figure 8 shows the effect of current on the pore pressure gradients at the upper seabed with a series of wave heights. The presence of a following-current makes the magnitudes of the maximum pore pressure gradients increase remarkably, while the opposing-current has the opposite effect. The relative difference of the pore pressure gradient caused by superimposing a following-current

Figure 8. Comparison of the pore pressure gradients variation with wave height between waves-alone condition, waves plus following-current condition and waves plus opposing-current condition ($T = 1.2$ s).

Figure 9. Comparison of the vertical distributions of the wave-induced seabed response versus soil depth under waves-alone condition with different wave periods ($H = 9.5$ cm).
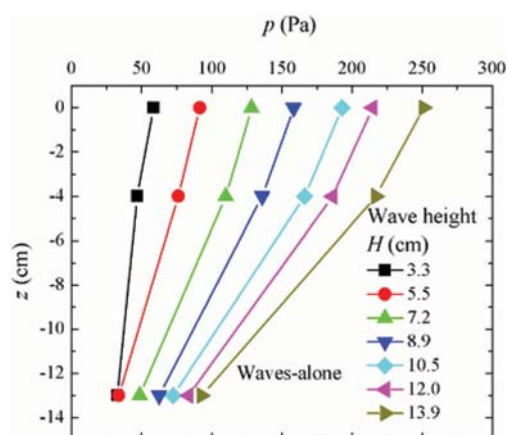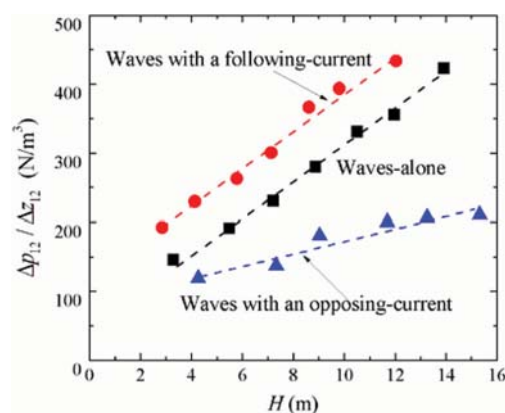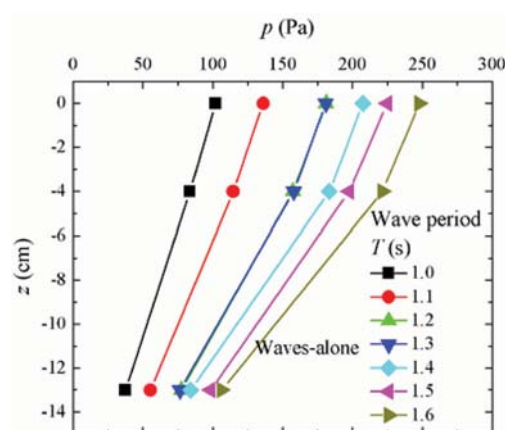

Figure 7. Comparison of the vertical distributions of the wave-induced seabed response under waves-alone versus soil depth between different values of wave heights ($T = 1.2$ s).

seems invariant with wave heights. The reduction of the gradient caused by the presence of a opposing-current becomes greater as the wave height increases.

The vertical distributions of the wave-induced seabed response versus soil depth under waves-alone condition with a series of wave periods are given in Figure 9. The seabed response increases as the wave height increases. As the decreasing rate of the seabed response along the soil depth varies with wave height, the rate reduces with the increasing depth for relatively small wave heights, while the rate increased for relatively bigger wave heights.
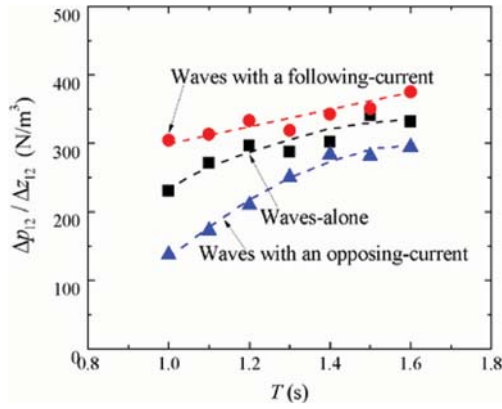
Figure 10. Comparison of the pore pressure gradients variation with wave period between the conditions of waves alone, waves plus following-current and waves plus opposing-current ($H_0 = 9.5$ cm).
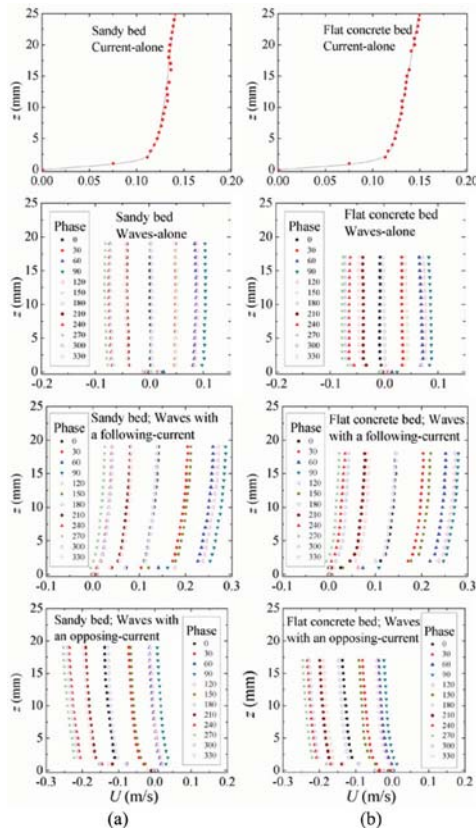

Figure 11. Comparisons of the velocity profiles under current alone, waves alone, waves plus following-current, and waves plus opposing-current between: (a) over sandy seabed; and (b) over flat concrete bed (Waves: $H_0 = 7.2$ cm, $T = 1.5$ s; current: $U_c = 0.20$ m/s & −0.20 m/s).

Figure 10 shows the effect of the current on the pore pressure gradients at the upper seabed with a series of wave periods. The effect of either a following-current or a opposing-current is much more significant for the waves with a comparatively shorter period. For example, the relative difference of the magnitudes of the maximum pore pressure gradients can reach more than 30% under the condition of $T = 1.0$ s, while the relative difference is only about 10% under the condition of $T = 1.6$ s.

3.3 *Effect of the seepage on the boundary layer velocity profiles*

The boundary layer velocity profiles under current alone, waves alone, waves plus following-current and waves plus opposing-current were measured both on the flat concrete bed and on the sandy bed, as shown in Figure 11. The velocity data in Figure 11 is the average value of the primary measured data. The velocity distributions over sandy seabed and flat concrete bed have no evident differences. The magnitude of the wave-induced pore pressure gradient is about 800 N/m³, approximately 9% of the buoyant unit weight of soil in the tests. It may be concluded that the wave-induced seepage has little effect on the boundary layer velocity profiles for the parameter range of the present experiment, probably due to the relatively small magnitude of the wave-induced pore pressure gradient.

4 CONCLUSIONS

The effect of current on the wave-induced seabed pore pressure response is experimentally investigated. Moreover, the influence of wave-induced seepage on the velocity profile of the boundary layer under combined waves and current is examined.

Based on the results of a series of experiments in a large flow-structure-soil interaction flume, the following conclusions are drawn:

1. The amplitude of the seabed response is basically greater under waves plus following-current than waves alone, while the amplitude of the response is smaller under waves plus opposing-current than waves alone. Thus the sand liquefaction is more likely to occur under waves plus following-current, while the opposing-current is beneficial to prevent the seabed from liquefying.
2. The relative difference of the pore pressure gradient caused by superimposing a following-current is invariant with different values of wave heights. The reduction of the gradient caused by the presence of an opposing-current becomes greater as the wave heigth increases. The effect

of either a following-current or a opposing-current is much more significant for the waves with a comparatively shorter period.

3. The wave-induced seepage has slight effect on the boundary layer velocity profiles for the examined hydrodynamic loads and the medium sands.

ACKNOWLEDGMENTS

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