CHAPTER ONE HUNDRED SIXTEEN

LABORATORY REPRODUCTION OF SEABED SCOUR
IN FRONT OF BREAKWATERS

by

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ABSTRACT

Mechanism of scour in front of breakwaters by standing waves in two
and three dimensions has been studied theoretically and experimentally
to clarify the experimental conditions by which the prototype behavior
could be best reproduced in laboratory. The phenomenal reproduction
of scour in laboratory is satisfactory if some conditions on the
characteristics of waves and bed materials are fulfilled. This enables
experimental approach to find out the optimum protection methods against
scour in front of breakwaters.

INTRODUCTION

Extensive prolongation of breakwaters in many ports in Japan has
sometimes caused severe scouring in front of breakwaters. In some
crucial cases, the size of scour has developed up to 6 meters in scour
depth and almost a hundred meters in scour length measured nomal to
breakwaters, threatening stability of breakwaters.

To work out the most effective protection methods against those
problems, model experiment could be an effective measure. However, no
confirmation has been made so far as to whether the phenomena in
prototype could be properly reproduced in laboratory.

The objective of the present study is to make clear the mechanism
of two and three dimensional scour in front of breakwaters by standing
waves through detailed measurement of velocities and bed material
movement, to find out the experimental conditions by which the prototype
behavior could be best reproduced in laboratory, and to examine the
reproducibility of model experiments.

The type of breakwaters constructed at deeper water depth is mostly
of caisson type composite breakwater. It has the advantages of
experiencing lesser wave pressures because they reflect waves in the
form of standing waves and also lesser wave forces upon rubble mounds
due to their lower crown height. In the composite breakwater, however,
the stability is frequently threatened by scour in front of breakwaters.

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   The process in which structural destruction due to scour is trans-
mitted would be in falling dominos manner as illustrated in Fig. 1.
The process must be checked at some stages so that countermeasures
which will be taken against scour are most effective and economical.
   In order to achieve the above purposes experimentally, the
conditions required for satisfying phenomenal similarity are examined
first of all by investigating the mechanism of bed material movement
on a flat bed, an artificially roughened bed and a movable bed.
   Based upon the required conditions for phenomenal similarity, it is
examined whether the size of scour large enough to affect on the
stability of breakwaters could be reproduced in laboratory.

        BED MATERIAL MOVEMENT ON A FLAT BED BY STANDING WAVES

   When progressive waves are reflected by a vertical wall perfectly,
a standing wave is produced resulting in the surface oscillation
containing loop at the wall and node at L/4 apart from the wall where
L is the wave length. In order to obtain the basic idea on the
mechanism of scour by standing waves, characteristics of bed material
movement on a flat bed are studied theoretically and experimentally
first of all.
   A knowledge of the fluid velocity distribution close to the bed is
of considerable importance. Figure 2 shows the results of the
measurement of the Eulerian drift velocity distribution with a laser-
doppler anemometer. It is clearly seen that there exists a thin layer
drift from node to loop near the bed and the opposite drift in the
upper layer, and this seems to coincide with the theoretical
distribution of a second order mean velocity by standing waves given
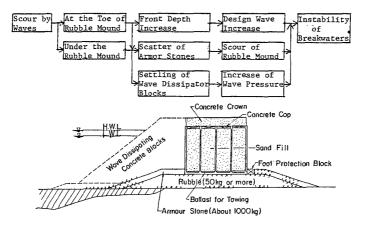by Longuet Higgins.

Fig. 1   The process in which structural destruction is transmitt-
          ed up to the main body of breakwater.

If bed materials are to move according to the drift near the bed, bed materials placed on a flat bed should move from nodes to loops according to Fig. 2, however, every materials whose specific gravity is 2.65 were observed to move from loops to nodes.

In order to clarify those contradictory phenomena, a theoretical consideration has been made as follows. Sand particles on a flat bed are not necessarily in the state of motion during a wave period but at a stand still at a certain moment because of the bottom friction. If the oscillatory movement of water particles is completely sinusoidal, no residual shift of sand particles would result after a wave period.

Actually, the motion of water particles is not sinusoidal because of the non-lineality of waves and a net shift of sand particles would result after a wave period.

The following equations of motion are formed;

$$dx_s/dt = u_s \qquad\qquad\qquad (1)$$

$$du_s/dt = 3C_d | u-u_s | \cdot (u-u_s)/4d(s+C_m) + 1/(s+C_m) \cdot du_0/dt$$

$$C_m/(s+C_m) \cdot du/dt \pm (s-1)/(s+C_m) \cdot \mu_f \qquad (2)$$

where,

x_s: Horizontal position of sand particles.

u_s: Velocity of sand particles.

u : Velocity of water particles in the boundary layer.

   (at $z = d/2$)

u_0: Velocity of water particles just outside of boundary

   layer.

d : Diameter of sand particles.

s : Specific gravity of sand particles.

C_d: Drag coefficient.

C_m: Virtual mass coefficient.

μ_f: Friction coefficient with the bottom.

The moment at which sand grains start to move from the rest is obtained by judging whether the sum of the first three terms in the right hand side of equation (2) exceeds the fourth term. Here, the coefficients were selected so that $\mu_{fs} = 0.5$, $\mu_{fm} = 0.1$, $C_d = 0.5$ and $C_m = 0.5$.

The velocity u of water particles is calculated by the following equation;

$$\partial u/\partial t = \partial u_0/\partial t + \nu \cdot \partial^2 u/\partial z^2 \qquad\qquad (3)$$
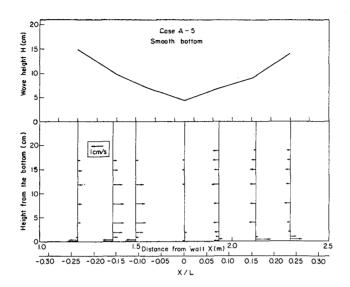
where,

ν : Kinematic viscosity.

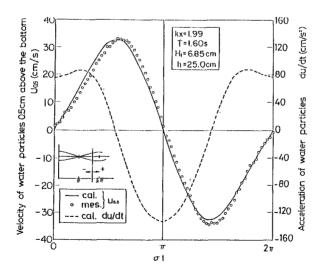Fig. 2 The Eulerian drift velocities measured by a laser-doppler anemometer.

Fig. 3 Periodical change of velocity and acceleration of water particles 0.5 cm above the bottom.

u_0 : Velocity of water particles just outside the boundary
         layer.

z : Height from the bottom.

   Figure 3 shows the periodical change of velocity and acceleration
of water particles 0.5 cm above the bottom calculated by third order
finite amplitude theory. The result of the measurement of water parti-
cle velocity is also shown in the figure. The velocity curve is
symmetric about zero point whereas the acceleration curve is not
symmetrical. It is seen that acceleration inbetween nodes and loops
exhibits much higher value in the direction from loops to nodes. This
results in the net shift of sand particles toward nodes from loops if
the particles are moved having bottom friction because initiation of
motion after a stand still is much earlier in this direction.
   The results of calculation of net shift of sand grain after a wave
period utilizing equation (1), (2) and (3) are shown in Fig. 4.
The velocity u of water particles in the boundary layer calculated by
equation (4) is distorted so that amplitude toward node is higher
than opposite phase. Furthermore, acceleration just outside the bound-
ary layer $\partial u_0/\partial t$ is distorted as already explained. As the result of
these distortions, velocity of sand grains u_s toward node is always
higher than the opposite direction, and this results in the residual
shift ΔX toward nodes as seen in the figure.
   Movements of sand particles on a flat bed were followed by a movie
camera and the results are compared with theory as shown in Fig. 5.
The rate of shift of sand particles in a wave period has coincided
fairly well with the theory.

         BED MATERIAL MOVEMENT ON AN ARTIFICIALLY ROUGHENED BED

   Mechanism of bed material movement on the movable bed for which
the scour problems actually occur may be of much difference from that
of a flat bed because of the roughness due to sand ripples. In order
to examine the effect of the roughness on the movement of bed materials,
experiments on the mechanism of bed material movement on the artifi-
cially roughened bed were carried out .   As shown in Fig. 6, two kinds
of roughness were utilized; obstacles of 1.0 cm and 0.5 cm in height
were placed at the equal intervals of 5.0 cm and 3.0 cm respectively
so that the steepness of artificial roughness is of 1/5 to 1/6 which
is the steepness of sand ripples commonly found. Bed materials of
various settling velocities were placed at the trough of artificial
roughness in the place between nodes and loops of standing waves.
   Figure 7 shows the results of the measurement of the Eulerian drift
velocities with a laser-doppler anemometer when the height of artificial
roughness is 1.0 cm.   If the velocity distribution is compared with
that in Fig. 2 in which the same wave condition is applied, it is
clearly seen that the thickness of drift layer near the bottom has
remarkably developed in Fig. 7. In such a velocity field, bed materials
once suspended would tend to move from nodes to loops,however, bed
materials having the influence of bottom friction would still tend to
move in the reverse direction due to non-linearity of waves as already
mentioned. Thus, characteristics of net bed material movement would
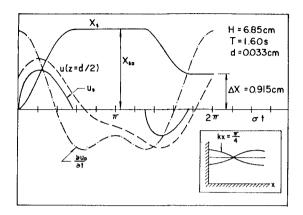
Fig. 4   Theoretical calculation of net shift of sand
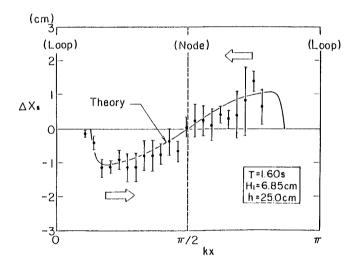   grains during a wave period.

Fig. 5   Comparison of experiment with theory on the net
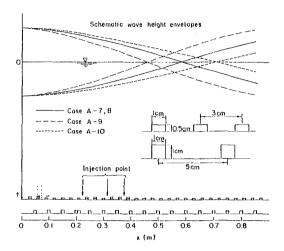   shift of sand grains during a wave period.

Fig. 6   Dimensions of artificial roughness.

depend on the relative importance between suspended load and bed load
and this was examined experimentally.

    Figure 8 shows the results of experiments on the movement of
various bed materials, that is, coal grains, finer sand and coarser
sand whose mediam diameters are 0.27 mm (specific gravity ≑ 1.58),
0.20 mm (s.g. = 2.65) and 0.33 mm (s.g. = 2.65) respectively.

    After the wave action of almost two minutes, the volumes of those
materials in each trough of artificial roughness were measured. The
volume V_L of the portion which moved toward loops and the volume V_N of
the portion which moved toward nodes were calculated, and the direction
of net movement of bed materials was judged by examining whether the
value of V_L/V_N exceeded one or not.   If $V_L/V_N>1$, it means that the
direction of net movement is from nodes to loops and this is called
L-type movement, and if $V_L/V_N<1$, it means that net movement direction
is from loops to nodes and this is called N-type movement.

    L-type movement will appear when suspended load is predominant and
transported due to the drift from nodes to loops as already seen in
Fig. 7. Therefore, relative velocity of water particles u_b/w will be
a dominant parameter for the appearance of L-type movement where u_b is
the amplitude of water particle velocity at the bottom for incident
waves and w is the settling velocity of bed materials.

    The reason for the appearance of N-type movement could be considered
as follows.   As already explained, bed materials on a flat bed are
moved from loops to nodes so long as the bed materials experience the
effects of bottom friction and this will also applicable in the present
case.   Another reason for the appearance of N-type movement will be
the difference of the vortex formation in the wakes of the obstacles
of artificial roughness. Votices are carried back over the obstacles
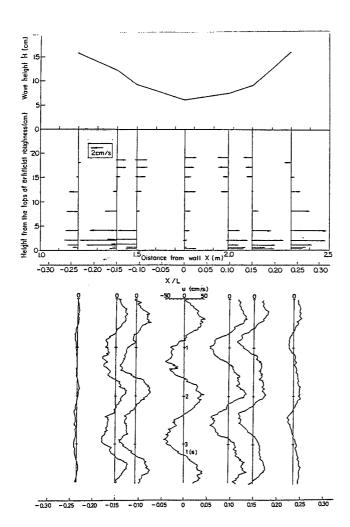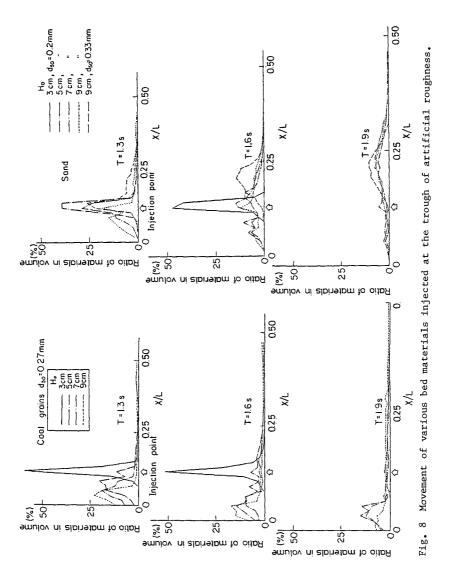
Fig. 7   (Top) Eulerian drift velocities when artificial
                 roughness is 1.0 cm.
           (Bottom) Change of water particle velocity with time
                 at each corresponding position.

Fig. 8 Movement of various bed materials injected at the trough of artificial roughness.

and then out over the trough when the flow reverses and this process is
repeated under the oscillatory motion of water particles. If the motion
of water particles is sinusoidal, development of vortices on the both
sides of obstacles will be the same and there will be no contribution
to the net material movement onshoreward or offshoreward. As seen in
Fig. 3 and Fig. 7 in which the changes of water particle velocities
with time between nodes and loops of standing waves are illustrated,
however, the time from a zero velocity to a maximum velocity is actually
longer when the flow is toward loops than toward nodes whereas the ampl-
itudes of the velocity is almost the same in both directions.   It is
apparent that more vortex development will take place if the time for
development is longer on the premise that the amplitudes in both direc-
tions are the same. Consequently, vortex development is always greater
in the loop side of the obstacles than the other side and much materials
will be enrolled in the vortices of loop side and carried out over the
obstacles toward nodes when the flow reverses. This would lead to a net
bed material movement from loops to nodes resulting in N-type movement.

    Thus, at any rate, appearance of N-type depends on the non-linearity
of waves and this is expressed in the Ursell Number $U = HL^2/h^3$ where,
H, L and h are wave height, wave length and water depth respectively.

    The experimental results of the relations between V_L/V_N versus u_b/w
are plotted with $U = HL^2/h^3$ in parameter as shown in Fig. 9. From the
figure, L-type tends to appear when the relative velocity u_b/w increases
for a given Ursell Number and N-type tends to appear when the Ursell
Number increases for a given relative velocity. Those charateristics
of the appearance of L-type movement and N-type movement seem to endorse
the understanding on the mechanism of bed material movement described
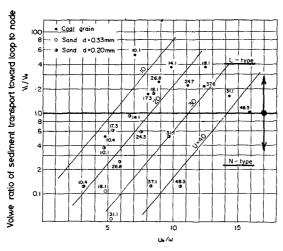above.

Fig. 9   L-type and N-type appearance in the bed material
         movement on a fixed bed.
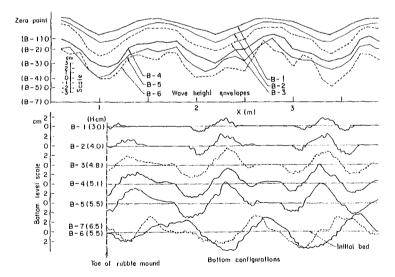   The parameters show the Ursell Number.

TWO DIMENSIONAL SEABED SCOUR BY STANDING WAVES

    If L, N-type movement of bed materials as observed in artificially
roughened fixed bed exists also for the movable bed, two types of seabed
scour will appear accordingly.
    Figure 10 shows the results of experiments of sea bed scour when
coal grains(median diameter d_{50} = 0.27 mm, specific gravity s.g. = 1.58)
are utilized as bed materials. Waves from 3.0 to 6.5 cm in wave height
and 1.6 sec in wave period were acted on the breakwater wall for 6 hours
in the cases from (B-1) to (B-6). Since the rubble mound of breakwater
had the berm width of 10 meters (25 cm in the model as model scale was
1/40 of the prototype), only the offshore side from the toe of rubble
mound is illustrated in the figure.
    Comparison of bottom profiles with wave envelopes depicts that accu-
mulation of bed materials takes place at nodes and erosion takes place
inbetween nodes and loops when wave height is smaller than 5.5 cm, that
is, in the cases of (B-1) to (B-5), whereas accumulation takes place
at loops and erosion takes place at nodes when wave height is much high-
er, that is, in the cases of (B-6) and (B-7). A geometrical considera-
tion of the balance of volumes of bed materials would indicate that the
cases of (B-1) to (B-5) are the consequences of N-type movement and the
cases of (B-6) and (B-7) are the consequence of L-type movement.
    Similar experiments on the mode of seabed scour was carried out uti-
lizing finer sand (d_{50} = 0.20 mm, s.g. = 2.65) and coarse sand (d_{50} =
0.33 mm, s.g. = 2.65). In the finer sand, sea bed scour due to both

Fig. 10   Bottom configurations under standing waves of various
          wave heights.
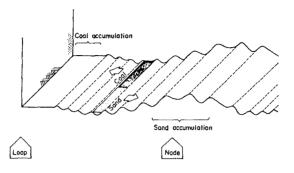
Fig. 11   Difference of the direction of movement
           between coal grains and coarser sand in
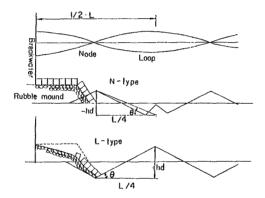   the same velocity field.

Fig. 12   Schematical illustration of two types
           of scour.

L-type movement and N-type movement appeared whereas in the coarser sand,
seabed scour of only N-type movement appeared. The mechanism of the
appearance of N-type movement and L-type movement in the movable bed
could be considered similar to that in the artificially roughened fixed
bed. An interesting experiment was carried out for a better understand-
ing of the appearance of two types of scour mode in the movable bed.
As shown in Fig. 11, sand ripples were formed first of all by acting
waves of 7 cm in height and 1.6 sec in period for 50 minutes with the
water depth of 25 cm and then the movable bed was fixed hard with glue
so that no deformation would take place any more. In a trough of sand
ripples between nodes and loops, sand of 0.33 mm in median diameter and
2.65 in specific gravity, and also coal grains of 0.27 mm in median dia-
meter and 1.58 in specific gravity were placed half in half within the
flume width as shown in the figure and waves were again acted .
As seen in the figure, coal grains which are the lighter materials moved
toward loop exhibiting L-type movement whereas the coarser sand moved
toward node exhibiting N-type movement. In the present case, the drift
distribution must have been the same and the only difference is the
settling velocity between coal grains and coarser sand. This fact seems
to endorse that the mechanism for the artificially roughened bed is also
applicable for the movable bed.
     Thus, existence of two types of scour, that is, L-type scour due to
L-type movement and N-type scour due to N-type movement has been confir-
med as shown in Fig. 12.   A simple geometric inspection of scour shape
with respect to the size of the rubble-mound of usual brakwaters would
indicate that the scour of L-type is more critical for the stability
of breakwaters.
     Figure 13 shows the experimental results of the critical appearance
of L, N-type scour in the movable bed where ordinate and abscissa show
the relative velocity and the Ursell Number respectively.   The numbers
attached on the circles and triangles in the figure show the comprehens-
ive slope of the score holes, that is, $\tan \theta = (\pm h_d / (L/4))$.
     The results of experiments by Xie are also shown in the figure. The
relative velocity is more critical for the appearance of L-type or N-ty-
pe scour than the Ursell Number where those parameters were equally
important in the fixed bed.
     The most important fact in the figure will be that L-type scour
appears when the relative velocity u_b/w exceeds more or less the value
of ten. Since the relative velocity normally exceeds tens or twenties
in the prototype, the scour in prototype would have the scheme of L-type
scour and thus, the model experiments of scour in front of breakwaters
by standing waves cannot be reproduced unless $u_b/w > 10$ is satisfied.
     Utilization of finer materials would reproduce more remarkable scour
which is indispensable for the examination of effective protection meth-
ods.
     Figure 14 shows an example of scour which is reproduced utilizing
fine sand of 0.06 mm in median diameter.   The scale of the model was
1/50 and waves of 12 cm in height and 1.4 sec in period were acted on
the composite type breakwater at the depth of 30 cm.
     A remarkable damage of rubble mound would take place when the node
of standing waves comes near the toe of rubble mound.   It will have a
lesser effect of scour if wave period is very long so that the first
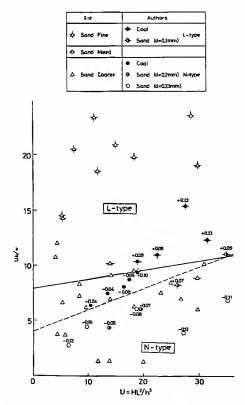node of standing waves comes much offshore of the toe of rubble mound.

Fig. 13   Critical appearance of N,L-type scour in the
          movable bed

Fig. 14   An example of two dimensional scour

THREE DIMENSIONAL SEABED SCOUR

Diagonal action of waves on breakwaters would result in the drift
parallel to the breakwaters and this will affect on the scour. Many
researchers have studied on the mass-transport by diagonal standing
waves experimentally and theoretically. Authors have also made calcu-
lations of three dimensional mass-transport by diagonal partial stand-
ing waves in the similar manner and confirmed quantitative validity of
the theory through laboratory study.

Those results indicated that mass-transport diverges at nodes and
converges at loops forming converged flow parallel to the breakwaters.
With roughened bottom, the thickness of the drift due to mass-transport
near the bottom was observed to increase having no basic change of
directions. Those results depicts that in three dimensional scour
under diagonal waves, bed materials at nodes are transported from nodes
to loops and also toward downstream parallel to breakwaters so long as
suspension is predominant.

Actually, in three dimensional experiments with regular waves,
scour took place at nodes as observed in two dimensional cases. The
definite difference from two dimensional cases was that the average
elevation of the bottom was eroded down due to the transportation of
bed materials downstream along the breakwater. This resulted in the
remarkable scour near the tip of breakwater and somewhat heavier
accumulation in the downstream area along the breakwater.

Figure 15 illustrates the example of scour near the tip(upstream
area) of breakwater with the model scale of 1/40 when waves of 15 cm
in height and 1.6 sec in period were acted for 16 hours at 30 degrees
to the normal line of breakwater. The bed materials was sand of 0.13
mm in median diameter. The downstream bottom topography became much
complicated because of the effects of oscillations in the model basin
and also variation of wave height along the breakwater.

Those difficulty of producing uniform scour along the breakwater
which is the common feature found in prototype was considerably improved
when irregular waves are utilized.

Figure 16 illustrates the result of experiments in which waves of
8 cm and 1.3 sec in significant wave height and period respectively
were acted for 11 hours at 30 degrees to the normal line of breakwater.
It is seen that the scour took place at nodes of irregular standing
waves and no significant scour took place in the offshore area.
Furthermore, the scour is most remarkable near the tip of breakwater
and gragually diminishes toward downstream area along the breakwater.

In the figure, bottom topography in front of breakwater of Fukui
Port facing to Japan Sea is illustrated. Comparison of the scour shape
between model and prototype would depict that reproduction of scour in
front of breakwater by standing waves is quite satisfactory.

CONCLUSIONS

1. Due to the non-linearity of waves, bed materials placed on a flat
    bed move from loops to nodes of standing waves so long as the
    materials have the effects of bottom friction.

Fig. 15   An example of seabed scour near
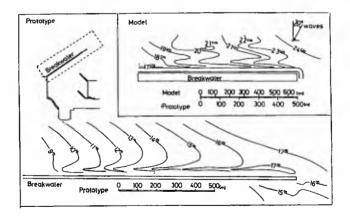   the tip of breakwater.

Fig. 16   Comparison of scour shape between model
          and prototype.

2. There are two modes of bed material movement under standing waves when the bottom has the artificial roughness, that is, L-type movement in which bed materials move from nodes to loops and N-type movement in which bed materials move from loops to nodes. Criteria of appearance of those types depend on the relative velocity u_b/w and the Ursell Number $U(=HL^2/h^3)$.
3. In the movable bed, two types of scour due to standing waves exist accordingly, that is, L-type scour in which bottom is scoured at nodes and accumulated at loops and N-type scour in which bottom is scoured inbetween nodes and loops and accumulated at nodes.
4. In order to reproduce the prototype scour in laboratory, it is required that the relative velocity u_b/w exceeds the value of ten.
5. The scour whose size is large enough to affect on the stability of breakwater can be reproduced if fine materials are utilized.
6. Reproduction of three dimensional scour is satisfactory if irregular waves are utilized.

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