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Generalized time scale for wave-induced backfilling beneath submarine pipelines

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Abstract

This paper presents 25 new laboratory experiments involving the wave-induced backfilling of wave-induced scour holes beneath submarine pipelines (so-called wave-to-wave backfilling scenarios). The experiments complement the previous 8 wave-to-wave backfilling experiments of Fredsøe et al., as well as recent current-to-wave backfilling experiments of Bayraktar et al. It is found that the wave-induced backfilling time scale is generally an order of magnitude larger than for scour, and is relatively insensitive to the initial (current- or wave-induced) pre-backfilling scour profile. Based on this, the data sets involving wave-induced backfilling are collectively analyzed, resulting in a new generalized expression for estimating the wave-induced backfilling time scale beneath pipelines in the live-bed regime. This expression accounts for primary dependence on the Shields parameter, as well as secondary dependence based on the difference between the (estimated or known) initial and expected final equilibrium scour depth due to the backfilling wave condition.

Keywords: Scour, Backfilling, Pipelines, Sediment transport, Time scale, Steady current, Waves

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11 1. Introduction

12 Submarine pipelines are commonly used to transport water, waste water,
 13 oil, natural gas and other hydrocarbons across marine environments. Given
 14 the often-hazardous contents carried, the failure of a submarine pipeline may
 15 have catastrophic effects on the environment, and ensuring their structural
 16 integrity is therefore of high importance. In the marine environment, when
 17 submarine pipelines are exposed to combined wave and/or current flows,
 18 scour can develop around the pipe, leading to suspended free spans which
 19 in turn increase stress and contribute to structural fatigue. Moreover, if
 20 scouring conditions are followed by more mild wave conditions, backfilling
 21 may occur. It is hence of engineering interest to be able to predict the
 22 temporal evolution of the scour depth beneath pipelines in both scour, as
 23 well as backfilling, conditions. At a minimum, this requires methods for
 24 predicting equilibrium scour depths, as well as the so-called time scales, in
 25 a variety of conditions.

26 Local pipeline scour and/or backfilling processes due to current and/or
 27 waves have been commonly studied both experimentally (*e.g.* Sumer and
 28 Fredsøe, 1990; Fredsøe et al., 1992; Zhang et al., 2016; Bayraktar et al.,
 29 2016) as well as numerically (*e.g.* Brørs, 1999; Liang and Cheng, 2005;
 30 Kazeminezhad et al., 2012; Zanganeh et al., 2012; Fuhrman et al., 2014;
 31 Larsen et al., 2016). Leckie et al. (2016) likewise studied the time scale of
 32 sedimentation around pipelines (*i.e.* involving the accumulation of sediment
 33 adjacent to a pipeline). A recent review of pipeline-seabed interactions can
 34 be found in Fredsøe (2016). At present, widely-used expressions exist for pre-
 35 dicting the equilibrium scour depth due to both currents and waves (Sumer
 36 and Fredsøe, 1990) as well as their combination (Sumer and Fredsøe, 1996).
 37 Similarly, methods for predicting the scour time scale in pure waves and
 38 currents are provided by Fredsøe et al. (1992), as well as their combination
 39 by *e.g.* Larsen et al. (2016). Considering wave-induced backfilling, Fredsøe
 40 et al. (1992) likewise found that equilibrium scour depth corresponded sim-
 41 ply to that predicted by the new wave condition alone, and this finding is
 42 backed by later numerical (Fuhrman et al., 2014, who also extended this to
 43 other profile features) and experimental (Bayraktar et al., 2016) studies. An
 44 experimentally-based expression for predicting the wave-induced backfilling
 45 time scale following pure-current scour beneath pipelines (so-called current-
 46 to-wave backfilling scenarios) has been provided recently by Bayraktar et al.
 47 (2016).

48 Presently, however, no such expression has been proposed for the more
 49 complicated wave-to-wave backfilling counterpart, though a limited num-

ber of experiments involving such scenarios have been provided by Fredsøe et al. (1992). The present work aims to fill this gap by first presenting several new experiments involving wave-to-wave backfilling scenarios, adding significantly to the data set of Fredsøe et al. (1992). The collective data sets involving wave-induced backfilling (the present work, Fredsøe et al., 1992; Bayraktar et al., 2016) will then be analyzed, resulting in a new expression suitable for the general engineering prediction of the wave-induced backfilling time scale.

2. Experimental setup

Experiments were conducted in a 22 m long and 0.6 m wide wave flume with glass walls in the Hydraulics Research Laboratory at the Technical University of Denmark. Within the flume a sand pit was constructed having length 8.4 m, width 0.6 m, and thickness 0.11 m. The median diameter of the sand is $d = 0.18$ mm. Both ends of the sand pit are stabilized by a wall of bricks having the same height as the sand pit. At the end nearest the piston-type wavemaker a sloped transition has been constructed of crushed stones. The other end extends all the way to the passive wave absorber (wave breaker type), which dissipates the wave energy and hence minimizes reflections. In all experiments the water depth is kept constant at $h = 40$ cm above the sand pit. Solid PVC rod pipelines with three different diameters ($D = 3, 5$, and 7 cm) have been utilized. The setup described above is illustrated in elevation (side) and plan view sketches provided in Figure 1. To ease smoothing of the bed at the beginning of each experiment, the sand pit was equipped with two 0.012 m wide plywood guide leveling boards having the same standing height as the sand pit (0.11 m). These spanned from the brick sections at each outer end of the pit to approximately 0.5 m from the pipeline center on either side, to ensure that these do not influence the scour or backfilling process in the near vicinity of the pipeline.

Surface elevations have been measured with two resistance type wave gauges on either side of the pipeline. These are placed just up- and downstream of the pipeline, which have been collectively used to approximate the wave condition (characterized by the significant wave height H_s and peak period T_p) at the pipeline.

The scour and the backfilling process around the pipeline has been monitored using video recordings made with a Nikon D5600 camera. The camera was mounted outside the glass-walled flume, directly in line with the pipeline (see Figure 1b). The (relatively rapid) scour process has been recorded directly with video (1080p with at least 50 fps). The (slower) backfilling

process has alternatively been recorded with a time-lapse function in the camera, wherein a high resolution picture is taken every second, which are then compiled into a video. This has been necessary due to memory limitations within the camera.

A $1\text{ cm} \times 1\text{ cm}$ grid was taped to the outer flume wall as an approximate reference for monitoring the scour development. It is recognized that measurements based directly on the grid would be slightly erroneous (approximately 10%) when naively translated directly to the scour depth (and other lengths) on the inside of the glass. This is due to the placement of the grid on the outside of the flume wall, combined with the finite glass thickness and the non-telecentric camera lens. Based on the known pipeline dimensions, the discrete grid values from the outside glass used in post-processing have been calibrated such that they represent the actual vertical and horizontal locations inside the flume, and it is these corrected values which are exclusively reported in what follows. This is mentioned merely in the interest of full scientific disclosure. The level of these modifications (again approximately 10%) is well within the typical scatter of the results, and can hence be considered largely inconsequential.

Bayraktar et al. (2016) performed their current-to-wave backfilling experiments using both regular and irregular waves. They found considerably more scatter in the results utilizing regular waves, presumably due to the more organized nature of reflections in such circumstances. Based on this experience, and the fact that they are more realistic, the present work will only consider scour and backfilling induced by irregular wave fields. The irregular wave fields were based on the JONSWAP spectrum, which will again be characterized by the significant wave height H_s and peak period T_p in what follows.

The experimental protocol followed was as follows: Prior to each experiment, the flume was drained, the pipeline removed, and the bed leveled. The flume was then filled slowly with water until the desired water depth (0.4 m above the sand pit) was reached. The pipeline was then mounted such that its bottom was flush to the sand after the flume was filled, to avoid any scour due to smaller streams and waves caused by the filling process. Resistance type wave gauges were mounted and calibrated just prior to the experiment being started. Following the initial setup, the pipelines were subjected to a two stage process: First, an initial (relatively large in terms of the Keulegan-Carpenter number, KC , to be defined in what follows) wave field was generated, inducing scour beneath the pipeline. These conditions were maintained until approximate equilibrium scour conditions are reached. Second, the pipeline was subjected to a wave field resulting in

a smaller KC , hence inducing backfilling beneath the pipeline, and the new wave condition was maintained until equilibrium conditions were reached. Some example pictures taken during both scour and backfilling stages are presented in Figure 2. Incidentally, these pictures also demonstrate development of ripples both up- and down-stream of the pipeline, which may be regarded as a scale effect (at full scale, the Shields parameter may be sufficiently large to wash them out). These features are commonplace, however, within live-bed laboratory scale pipeline scour experiments, and it is not possible to avoid their development. (Better understanding of their isolated effects would seemingly require further comparison with full scale studies, either in larger wave flumes or with computational models.)

Following the scour and backfilling tests, with the pipeline removed, the wave fields were repeated and velocities at the location corresponding to the pipeline center were measured with Laser Doppler Velocimetry (LDV) equipment. This was to enable use of the actual wave induced near-bed velocities to be utilized in the parameterization of the backfilling time scale. The equipment utilized for this purpose was a Dantec Dynamics system consisting of a diode pumped solid state (DPSS) 532 nm laser, FiberFlow optics with a 60 mm probe fitted with a 310 mm focal length front lens, Burst Spectrum Analyser (BSA) processor, and BSA Flow Software version 5.02.

3. Results

3.1. Scour depth time series and profiles

A total of 25 wave-induced scour and backfilling sequences have been performed, where the conditions for the initial scour stage (variables subscripted with 0) are provided in Table 1, and those for the subsequent backfilling condition (variables subscripted with f) in Table 2. Here the significant wave height H_s is taken as the mean of the largest third of the waves, and the peak period T_p is determined from smoothed spectra computed from the measured free surface elevation time series. Based on the LDV velocity measurements, the near-bed velocity scale will be defined, following Sumer and Fredsøe (2002), as

$$U_m = \sqrt{2}\sigma_U \quad (1)$$

where σ_U is the root-mean-square of the orbital velocity U measured at the original pipeline center position. The Keulegan-Carpenter number KC is defined as

$$KC = \frac{U_m T_p}{D} \quad (2)$$

where T_p is the peak wave period. The characteristic (far field) Shields parameter is defined as

$$\theta = \frac{U_{fm}^2}{g(s-1)d} \quad (3)$$

where g is the gravitational acceleration, $s = 2.65$ is the relative sediment density, and U_{fm} is the undisturbed friction velocity defined by

$$U_{fm} = \sqrt{\frac{f_w}{2}} U_m \quad (4)$$

Here f_w is the wave friction factor, which is taken as the maximum of those approximated for laminar, smooth-turbulent (after Fredsøe and Deigaard, 1992), and rough-turbulent (after Fuhrman et al., 2013) regimes:

$$f_w^{laminar} = \frac{2}{\sqrt{Re}} \quad (5)$$

$$f_w^{smooth} = 0.035 Re^{-0.16} \quad (6)$$

$$f_w^{rough} = \exp \left(5.5 \left(\frac{a}{k_s} \right)^{-0.16} - 6.7 \right) \quad (7)$$

In the above the Reynolds number is defined as

$$Re = \frac{U_m a}{\nu} \quad (8)$$

where $a = U_m T_p / (2\pi)$ is a scale of the free stream particle orbital amplitude, the kinematic viscosity taken as $\nu = 10^{-6} \text{ m}^2/\text{s}$, and where $k_s = 2.5d$ is taken as Nikuradse's equivalent sand roughness.

The measured time series of the scour depth S beneath the pipeline center during both initial scour and subsequent backfilling stages are presented in Figure 3. Here the crosses correspond to measurements during the initial scour stage ($t < 0$), and the dots correspond to measurements during the backfilling stage ($t \geq 0$), where $t = 0$ defines the time where the second (backfilling) wave condition is introduced. Additionally, the exponential time function from Sumer et al. (2013)

$$S(t) = S_f + (S_0 - S_f) \exp \left(-\frac{t}{T_b} \right) \quad (9)$$

is depicted as the solid lines during the backfilling stage, where S_0 is the initial (pre-backfilling) scour depth at $t = 0$, S_f is the final equilibrium

184 scour depth found during the backfilling stage, and T_b is the dimensional
185 backfilling time scale. This is calculated via integration as in Fuhrman et al.
186 (2014):

$$T_b = \int_0^\infty \frac{S - S_f}{S_0 - S_f} dt \quad (10)$$

187 As seen, the exponential backfilling curve provides a quite reasonable ide-
188 alization for most of the cases. Examples demonstrating the observed pre-
189 and post-backfilling scour profiles can be seen in Figure 4 (snapshots) and
190 Figure 5 (corresponding digitized profiles).

191 For the purposes of parametrization, the backfilling time scale is non-
192 dimensionalized in the manner suggested by Sumer and Fredsøe (2002):

$$T_b^* = \frac{\sqrt{g(s-1)d^3}}{D^2} T_b \quad (11)$$

193 with the resulting values listed in Table 2. As an initial check of the present
194 experiments, as well as those performed previously for wave-to-wave back-
195 filling by Fredsøe et al. (1992), the scour depth taken at the end of the scour
196 stage S_0 as well as the equilibrium value found during the backfilling stage
197 S_f are plotted versus KC in Figure 6. Also shown is the regression equation
198 of Sumer and Fredsøe (1990):

$$\frac{S}{D} = 0.1\sqrt{KC} \quad (12)$$

199 which is based on their own experiments as well as from Lucassen (1984). As
200 seen, both the scour and backfilling equilibria from the present experiments
201 follow this equation reasonably. Hence, the present experiments are in line
202 with the conclusion of Fredsøe et al. (1992), that the scour depth following
203 a change in flow conditions will tend to a new equilibrium based solely
204 on the new wave condition. This conclusion is similarly backed by other
205 experimental (Bayraktar et al., 2016; Zhang et al., 2016, 2017) and numerical
206 (Fuhrman et al., 2014; Bayraktar et al., 2016) research.

207 Fuhrman et al. (2014) also found that the equilibrium bed profiles (i.e. not
208 just the scour depth) that developed from scour and backfilling with the
209 same KC were also quite similar. In their case this was checked using
210 computational fluid dynamics simulations (based on the model developed
211 by Jacobsen et al., 2014) of scour and/or backfilling with exactly the same
212 KC and θ . As an additional check of this finding, some examples depict-
213 ing the final scour and backfilling bed profiles developed under similar KC
214 are depicted in Figure 7. While the various cases compared do not have

exactly the same KC and θ it is seen that the developed profiles (when non-dimensionlized using the diameter D) are indeed largely similar. This is especially apparent after noticing that some of the profiles appear to be mirrored about the centerline, e.g. Figure 7(c) shows profiles following scour and backfill with $KC \approx 13$, where a single similarly sized and placed shoulder has developed independently on either side of the pipeline. Hence, this comparison support the general conclusion that both the equilibrium scour depth, as well as developed features of the bed profiles, are largely governed by the most recent wave condition, generally in line with the contention of Fredsøe et al. (1992). Note that similar findings have also been reported for backfilling of scour holes around piles by Sumer et al. (2013).

3.2. Analysis of the wave-induced backfilling time scale

As previously mentioned, the principal aim of the present work is to formulate a general expression for predicting the time scale for wave-induced backfilling beneath submarine pipelines. On dimensional grounds, as discussed by Bayraktar et al. (2016), the non-dimensional time scale for so-called wave-induced backfilling scenarios may depend on three parameters:

$$T_b^* = f \left(KC_0 \text{ or } \frac{S_0}{D}, KC_f \text{ or } \frac{S_f}{D}, \theta \right). \quad (13)$$

Bayraktar et al. (2016) focused on so-called current-to-wave backfilling scenarios (i.e. scour due to pure currents followed by backfilling due to pure waves), which they argued would effectively reduce the dependence to two parameters, since the equilibrium pipeline scour due to currents is approximately constant (Sumer and Fredsøe, 2002):

$$\frac{S_0}{D} = 0.6 \quad (14)$$

Based on their experiments, they found that the current-to-wave backfilling time scale could be predicted reasonably by

$$T_b^* = 0.3\theta^{-5/3} \quad (15)$$

This is notably an order of magnitude larger than the time scale of scour, which is known to follow (Fredsøe et al., 1992):

$$T_s^* = \frac{1}{50}\theta^{-5/3} = 0.02\theta^{-5/3} \quad (16)$$

Secondary dependence on e.g. KC_f or S_f could not be convincingly detected in their data set. Both of the preceding two expressions have identical

power dependence on the Shields parameter, which is also consistent with other work predicting the scour time scale in more general wave-plus-current scenarios (Larsen et al., 2016; Zhang et al., 2017, in the latter case since $-5/3 \approx -1.5$).

Following these works, to begin characterizing the backfilling time scale, T_b^* from the present experiments, as well as those of Fredsøe et al. (1992), are plotted versus θ in Figure 8. While scattered (typical of scour and especially backfilling experiments, in the authors' experience), it is seen that these data reasonably follow the regression equation

$$T_b^* = 0.2\theta^{-5/3} \quad (17)$$

which can hence be considered as a first estimation of the wave-to-wave backfilling time scale. Although the initial pre-backfilling conditions are quite different (current- versus a wave-induced scour hole), this is notably quite similar to (15) from Bayraktar et al. (2016), and is again an order of magnitude larger than the scour time scale from (16), both of which are also shown on Figure 8 for comparison.

As an initial check for secondary dependence, following similar time scale analyses of Larsen et al. (2016) and Bayraktar et al. (2016), we have plotted $T_b^*\theta^{5/3}$ versus KC_0 and KC_f (not shown for the sake of brevity). Such plots do not convincingly support further parameterization based directly on either of these parameters alone. Similar plots and conclusions can be made if S_0 and S_f are directly utilized (also not shown for the sake of brevity).

As a second attempt, rather than e.g. utilizing S_0 and S_f (or KC_0 and KC_f) independently, we will instead consider their combined parameterization based on the change in scour depth $\Delta S = S_0 - S_f$. This is inspired by the simple physical notion that larger differences in initial and final scour equilibria may require longer time to backfill. Attempting to parameterize directly with ΔS , rather than with some similar combination of KC_0 and KC_f , is believed to be advantageous, as it enables direct use of the realized scour depths from the experiments (hence potentially reducing scatter). Moreover, it provides a form that is easily generalized to other scenarios, e.g. where the initial scour is due to pure current (as considered in the experiments of Bayraktar et al., 2016), wave-plus-current flow environments, or non-equilibrium conditions.

A plot of $T_b^*\theta^{5/3}$ versus $\Delta S/D$ for the previously considered data is provided in Figure 9. Additionally, in the spirit just mentioned, we likewise include the irregular wave experimental data set of Bayraktar et al. (2016)

for current-to-wave backfilling (these data are considerably less scattered than their regular wave experiments, as discussed previously). Both (17) and (15) are depicted as the horizontal lines, respectively spanning the region of $\Delta S/D$ on which they are based. The current-to-wave backfilling data set of Bayraktar et al. (2016) is generally to the right and slightly above the majority of the wave-to-wave data sets. This is expected due to the relatively large initial scour caused by the initial current; Indeed, Bayraktar et al. (2016) stated that (15) would likely serve as a reasonable upper limit for the backfilling time scale in wave-to-wave scenarios.

When viewed collectively, the combined data sets in Figure 9, which now span a far greater range in $\Delta S/D$ than in the previous experiments of Bayraktar et al. (2016), are seen to follow reasonably the regression curve

$$T_b^* = 0.6 \left(\frac{\Delta S}{D} \right)^{0.5} \theta^{-5/3}, \quad \Delta S = S_0 - S_f \quad (18)$$

which is depicted as the dashed-dotted line. This expression incorporates both the primary dependence on θ as well as the weaker secondary dependence on $\Delta S/D$. This expression matches closely both (17) and (15) in the range of $\Delta S/D$ where they were independently derived, effectively unifying these two similar expressions. Obviously, the scatter is still considerable. Potential reasons for this include: effects of far-field ripples, increased variability associated with a two-stage (i.e. scour followed by backfill) experimental procedure, and that we have reduced what is in principal a three parameter (i.e. Eq. (13)) dependency down to two (i.e. Eq. (18) based on θ_f and ΔS) for the sake of simplicity and practicality for engineering application.

Nevertheless, given the apparent general lack of sensitivity of the backfilling time scale to the initial scouring condition (pure waves or pure current), we therefore propose that (18) can be generally used to estimate the live-bed wave-induced backfilling time scale for submarine pipelines, at least within the experiment range of the Shields parameter considered (approximately $\theta_f \leq 0.2$). For this purpose S_0 may be taken as the (either expected or known) initial scour depth prior to backfilling e.g. based on (14) for scour due to pure current or (12) for scour due to pure waves (or other suitable time and/or flow based generalizations thereof for combined wave-current flows and/or non equilibrium conditions). Similarly, S_f can be taken as the expected equilibrium scour depth for the backfilling wave condition e.g. based on (12).

To demonstrate that (18) still works reasonably when applied using predicted, rather than measured, scour depths Figure 10 presents a similar plot

to Figure 9. In Figure 10, however, ΔS has now been estimated based only on equilibrium scour depths S calculated from (14) for current flows and from (12) for wave conditions. While the result is expectedly slightly more scattered than Figure 9, the resulting expression (18) still fits the combined three data sets reasonably as a whole.

4. Conclusions

This paper has presented a total of 25 new laboratory experiments involving the wave-induced backfilling of wave-induced scour holes (so-called wave-to-wave backfilling scenarios) beneath submarine pipelines. The new data set complements the limited number of experiments previously presented for such scenarios by Fredsøe et al. (1992), as well as the recent experiments by Bayraktar et al. (2016), who considered similar current-to-wave backfilling scenarios (wave-induced backfilling following current-induced scour).

The wave-to-wave backfilling data (i.e. the present experiments and those of Fredsøe et al., 1992) have been systematically analyzed, both in isolation, as well as in combination with the data of Bayraktar et al. (2016). This has resulted in a new and generalized expression for estimating the wave-induced backfilling time scale beneath submarine pipelines, given as equation (18) within the paper. The new expression accounts for primary dependence of the backfilling time scale on the Shields parameter, while also newly accounting for secondary dependence based on the difference in the initial and backfilling equilibrium scour depth. As the expression fits the existing data sets for both current-to-wave, as well as wave-to-wave backfilling scenarios, it is proposed to be appropriate for the engineering prediction of the wave-induced backfilling time scale, though some care must be utilized if the expression is applied outside of the experimental bounds.

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Table 1: Summary of test initial conditions and results for experiments involving irregular waves prior to change in wave condition.

Exp.	D	$H_{s,0}$	$T_{p,0}$	$U_{m,0}$	KC_0	Re_0	θ_0	S_0/D
	[cm]	[cm]	[s]	[cm/s]				
1	3	13.4	2.3	26.1	20.2	25230	0.148	0.42
2	3	14.4	2.2	25.5	19.1	23187	0.146	0.39
3	3	14.7	2.4	27.1	21.8	28184	0.155	0.41
4	3	14.9	2.4	27.1	21.8	28184	0.155	0.42
5	3	14.9	2.4	27.1	21.8	28184	0.155	0.46
6	3	15.0	2.5	27.1	22.7	29311	0.152	0.41
7	3	13.5	2.3	25.3	19.6	23613	0.142	0.42
8	3	14.8	2.5	27.1	22.7	29311	0.152	0.46
9	3	13.1	2.2	25.3	18.9	22770	0.145	0.42
10	3	14.8	2.4	27.1	21.8	28184	0.155	0.42
11	3	11.4	1.9	21.4	13.6	13904	0.134	0.37
12	3	11.4	1.9	21.4	13.6	13904	0.134	0.36
13	3	15.1	2.5	27.1	22.6	29157	0.153	0.47
14	7	12.9	2.2	23.7	7.6	19976	0.136	0.25
15	7	16.8	2.2	29.5	9.5	31038	0.183	0.31
16	7	16.0	2.2	34.5	11.0	42410	0.236	0.32
17	7	10.9	1.3	20.8	3.9	9013	0.156	0.18
18	7	10.4	1.3	20.0	3.7	8358	0.151	0.16
19	7	11.3	1.6	20.6	4.6	10630	0.142	0.16
20	7	12.3	2.0	25.5	7.4	21025	0.154	0.23
21	5	14.9	2.4	26.9	13.0	27728	0.153	0.30
22	5	10.4	1.4	14.8	4.2	4992	0.107	0.19
23	5	13.3	2.2	21.2	9.5	16097	0.122	0.31
24	5	12.8	2.3	25.3	11.8	23613	0.142	0.31
25	5	13.2	2.2	25.3	11.3	22770	0.145	0.31

Table 2: Summary of test final conditions and results for experiments involving irregular waves following a change in the wave condition.

Exp.	D	$H_{s,f}$	$T_{p,f}$	$U_{m,f}$	KC_f	Re_f	θ_f	S_f/D	$\Delta S/D$	T_b^*
	[cm]	[cm]	[s]	[cm/s]						
1	3	9.9	1.6	18.5	9.7	8519	0.127	0.28	0.14	4.04
2	3	8.7	1.4	16.5	7.7	6065	0.120	0.25	0.14	19.46
3	3	9.8	1.3	16.6	7.3	5769	0.125	0.26	0.15	11.06
4	3	11.3	1.7	22.9	13.3	14529	0.149	0.25	0.17	10.62
5	3	12.3	1.8	21.4	13.2	13495	0.136	0.32	0.14	4.91
6	3	11.3	1.7	22.9	13.3	14529	0.149	0.27	0.14	8.77
7	3	10.0	1.6	21.5	11.5	11809	0.145	0.28	0.14	3.34
8	3	11.5	1.8	22.5	13.9	14943	0.143	0.32	0.15	1.98
9	3	11.0	1.8	24.3	15.0	17324	0.154	0.30	0.12	3.55
10	3	7.8	1.1	12.9	4.7	2901	0.105	0.20	0.21	25.64
11	3	8.2	1.2	13.3	5.3	3386	0.104	0.23	0.14	14.86
12	3	9.9	1.6	21.5	11.5	11809	0.145	0.27	0.09	6.53
13	3	8.3	1.0	12.9	4.4	2711	0.109	0.25	0.22	24.64
14	7	10.0	1.7	17.3	4.2	8080	0.114	0.20	0.06	2.21
15	7	11.4	1.5	20.6	4.3	9888	0.147	0.19	0.12	3.49
16	7	13.1	1.7	25.5	6.2	17616	0.169	0.23	0.09	2.02
17	7	7.7	0.8	9.8	1.1	1237	0.093	0.11	0.06	14.41
18	7	9.1	1.1	13.3	2.2	3197	0.107	0.11	0.06	6.82
19	7	9.7	1.3	18.1	3.4	6795	0.136	0.13	0.04	6.40
20	7	8.6	1.4	9.8	2.0	2165	0.070	0.18	0.06	5.13
21	5	8.4	1.1	10.3	2.3	1861	0.084	0.18	0.12	8.80
22	5	6.8	1.0	6.5	1.3	693	0.055	0.15	0.05	40.84
23	5	10.1	1.3	14.2	3.7	4195	0.107	0.20	0.11	12.37
24	5	11.2	1.9	19.4	7.4	11452	0.121	0.25	0.06	14.93
25	5	8.3	1.1	10.3	2.3	1861	0.084	0.20	0.10	8.71

Figure 1: (a) Elevation and (b) plan view of the flume and the experimental setup.

Figure 2: Photographs showing ripple formation during experiments 3 and 6. Sub-plots (a) and (c) are prior to the change in wave condition i.e. during the initial scour stage and sub-plots (b) and (d) are after the the change in wave condition i.e. during the backfilling process.

Figure 3: Scour depth as a function of time where the scour part is induced by an initial wave spectrum until $t = 0$ followed by the backfilling part induced by a final wave spectrum for $t \geq 0$. All waves are irregular waves with a wave spectrum matching the JONSWAP spectrum.

Figure 3: (continued).

Figure 3: (continued).

(a) Experiment 13 ($D = 3$ cm) (b) Experiment 21 ($D = 5$ cm) (c) Experiment 15 ($D = 7$ cm)

Figure 4: Pictures demonstrating the bed profiles following the initial scour stage (left) and at the end of the backfilling stage (right).

Figure 5: Digitized bed profiles beneath the pipelines at the end of scour and backfilling stages for selected experiments. The selected cases are the same as those pictured in Figure 4.

Figure 6: Scour depth versus KC .

Figure 7: Comparison of scour and backfilled bed profiles with similar KC , where (a) $KC \approx 4.5$, (b) $KC \approx 7.5$ and (c) $KC \approx 13.0$.

Figure 8: Backfilling time scale T_b^* versus Shields parameter θ . It is emphasized that the time scale of scour T_s^* is a reference for comparison, not a target.

Figure 9: Backfilling time scale $T_b^* \theta^{5/3}$ versus $\Delta S/D$, where ΔS is directly based on measured values.

Figure 10: Backfilling time scale $T_b^* \theta^{5/3}$ versus $\Delta S/D$, where ΔS has been estimated from equilibrium scour depths S based on (14) for current flows and from (12) for waves.

Highlights for:**Generalized time scale for wave-induced backfilling beneath submarine pipelines****by Bastian et al.**

1. We study wave-induced backfilling of wave-induced scour beneath submarine pipelines.
2. 25 new experiments have been conducted at laboratory scale.
3. New and existing data are analyzed regarding the time scale of backfilling, T_b .
4. T_b is relatively insensitive to the initial (current- or wave-induced) scour hole.
5. A new generalized formula is proposed for the wave-induced backfilling time scale.