Experimental Observations of Tsunami Induced Scour at Onshore Structures

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Abstract

Tsunami inundation of the coastal environment can induce scour at structure foundations leading to failure. A series of experiments are made using a unique Pneumatic Long Wave Generator to generate tsunami wave periods of 25 - 147 s equating to 3 - 17.3 mins at 1:50 Froude scale. The waves propagate over a sloping bathymetry and impinge upon a square structure founded onshore in a flat sediment bed. Flow velocity, height and scour are recorded as a function of time during tsunami inundation. The rate of scour is observed to be time dependent. Equilibrium, which is not attained, is argued to be an inappropriate measure for time-dependent transient flows such as tsunami in which the flow velocity, depth and direction are variable. The maximum scour depth is recorded and critically is observed not to be equal to the final depth due to significant sediment slumping when flow velocities reduce in the latter stages of inundation. Current and wave scour predictor equations over predict the scour, while the ASCE 7-16 method under predicts. Comparisons with available data in the literature show longer inundation durations increase the amount of scour.

1 1. Introduction

Tsunami are commonly generated by under-sea mega-thrust fault motion or landslides, and contain sufficient potential energy to present a hazard to coastal life and the built environment. The 2004 Indian Ocean tsunami (IOT) resulted in over two hundred and fifty

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thousand casualties, \$9.9 billion in material damage losses and 1.7 million displaced persons 5 (Telford et al., 2006). The 2011 Great Eastern Japan Earthquake and Tsunami (TET) 6 resulted in over fifteen thousand casualties and an economic impact of over of \$211 billion in 7 direct damage (Kajitani et al., 2013). Scour is widely observed at, and often inferred as the 8 cause of failed coastal structures from post event field surveys (Chock et al., 2013; EEFIT, 9 2004, 2011; Mori and Takahashi, 2012; Yeh et al., 2007). In order to improve mitigation 10 against tsunami scour there is a need to understand its mechanism. This work presents 11 the first experimental study of onshore tsunami scour that considers tsunami inundation 12 time-scales appropriate to prototype. The results will pave the way to the development of 13 empirical models and to the validation of numerical models for predicting tsunami boundary 14 layers and scour at onshore structures. 15

When a structure is placed in a flow, scour may occur as a consequence of the boundary layer interaction with the sediment and structure. This causes flow separations, vortex formation and increased bed shear, all of which act to remove sediment until an equilibrium between the turbulent flow field and the bed level is attained. Figure 1 shows a schematic diagram of the main scouring phenomena in waves and currents.



Figure 1: A schematic diagram of the flow field around a cylinder in a current or waves where [1] is the incoming flow velocity profile, [2] is the surface roller [3], is the downflow, [4] is the horse-shoe vortex, and [5] are the wake vortices (see for example Melville and Coleman 2000).

Finding the equilibrium scour depth for a given structure under a given flow condition is of primary interest to the engineer because it informs design and mitigation. The scour depth d_{sc} is often given as a non-dimensional scour depth d_{sc}/D (where D is the structure diameter). In live-bed conditions (where flow velocity U exceeds the critical flow velocity for sediment motion U_c , d_{sc}/D is shown to be a function of Keulegan-Carpenter number ($KC = \frac{UT}{D}$) by Sumer et al. (1992) (where U is the maximum induced bottom orbital velocity and T is the period of oscillation). At low KC numbers, the scouring flow field may not exist for long enough in time and space to significantly contribute to the scour process (Sumer et al. 2001a), and equilibrium may take longer to attain. At high KC numbers, where the flow is quasi-steady or steady, the scouring flow field is able to fully establish and equilibrium may be attained more quickly.

A vast quantity of literature and research exists on scour depth in waves, currents and combinations of waves and currents interacting with *offshore* and *wetted* (where the structure is sited permanently in a flow) structures. This research pertains to engineering applications in bridge pier design, and offshore structures. Reviews are given by Sheppard et al. (2014) for bridge pier scour and Sumer et al. (2001b) for offshore scour.

In the case of tsunami induced scour, the literature is more limited and field investigations 37 of tsunami-induced scour are the primary source of scour data. Post-tsunami investigations of 38 scour include Wilson et al. (2012) in harbours, Tonkin et al. (2013) at roads and structures, 39 and Bricker et al. (2012) at coastal defences. Such retrospective investigations are few 40 in number, geographically localised and infer only post-tsunami scour depths, extents and 41 volumes; they are unable to provide systematic elucidation of the processes and mechanisms 42 of scour evolution. As will be shown, the observed post-tsunami scour depth may not be 43 equivalent to the maximum scour depth, and hence the use of such data may lead to non-44 conservative underestimations of the scour depth. 45

Experimentally, Yoshii et al. (2017) and Yoshii et al. (2018) investigated tsunami inun-46 dation and sediment transport and deposition in the coastal hinterland using two large wave 47 flume studies. However, laboratory investigations of onshore tsunami scour at structures 48 are very limited. Tonkin et al. (2003) uses solitary waves to represent tsunami at a circular 49 cylinder. Nakamura et al. (2008) uses a combination of solitary and 'long waves' (with a 50 maximum T = 14 s) for tsunami scour at a square cylinder. The solitary wave assump-51 tion does not allow for the period and length of the wave to be set independently, leading 52 to unrealistic waveforms when scaled up to prototype (Madsen et al., 2008). Therefore, 53 the appropriateness of the wave periods adopted in these investigations is limited, and may 54 not be representative of prototype tsunami inundation. Nevertheless, Tonkin et al. (2003)'s 55 experiments have been numerically simulated and applied to scour at bridge piers by Pan 56 and Huang (2012) and this methodology is cited in the ASCE (2016) Chapter 6: 'Tsunami 57

Loads and Effects' design standards. Lavictoire (2014), Shafiei et al. (2015), Mehrzad et al. 58 (2016) and Jayaratne et al. (2016), use a dam break method to generate tsunami-like bores. 59 However, while bores may form on the surface of a tsunami wave as a consequence of soliton 60 fission, for example, they represent only a small fraction of the tsunami period. As observed 61 in experiments by Foster et al. (2017) and McGovern et al. (2018), when realistic tsunami 62 periods are generated offshore, bore formation is rare, being tied to wave steepness λ/a , 63 where a is the wave amplitude and λ is the wavelength. As described in McGovern et al. 64 (2018) in an experimental study of tsunami runup, λ/a is extremely large for tsunami as 65 compared to bores and shorter waves. They define a 'Relative Slope Length' parameter 66 $\lambda \sin(\beta)/d$ (where β is the angle of the slope and d is the water depth at the point of wave 67 definition) which describes the ratio of the length of the wave to the length of the slope over 68 which it travels. For long waves such as tsunami, the parameter describes a situation where 69 the wave is much longer than the slope and, therefore, shoaling is limited. 70

The scour research listed above, although addressing a multitude of different scenarios, can be grouped together by KC. As $KC \to \infty$ the oscillation is negligible and the flow is a steady current where $\frac{du}{dh}(t) = 0$ (where u and h are the instantaneous flow velocity and water height at the structures' location respectively and t is time). At low KC, $\frac{du}{dh}(t)$ is cyclic around 0 over a period defined by T.

Tsunami are characterised by periods of ≈ 90 s - 2 hrs (Brown, 2013) and their long 76 periods translate into very long inundation events over land. Over shorter time scales, they 77 can be assumed to exhibit quasi-steady currents (Foster et al., 2017). They are, however, 78 cyclic over their defined period T, exhibiting variable flow velocities and inundation heights 79 on land. The influence of a cyclic flow such as a tsunami on the boundary layer will be a 80 combination of that of steady flows and waves. This is corroborated numerically by Larsen 81 et al. (2017) and experimentally by Larsen et al. (2018) for tsunami induced scour at scaled 82 offshore wind turbine monopiles. Therefore, it may be useful to describe tsunami by KC83 number when investigating its effect on scour. 84

Figure 2a shows a diagram of the model scale KC numbers investigated in the literature together with those for the experiments presented in this paper. KC number values between 50 and 1500 are expected for tsunami inundation flows, based on observations of the IOT and TET (flow velocity of ≈ 5 m/s full scale, Fritz et al. 2006, D = 10 m and a maximum period based on the TET of T = 1260 s, Kawai et al. 2013). On Figure 2a, it is observed that only the current experiments and Larsen et al. (2018) present tsunami specific studies with KC numbers in this range.

Figure 2b shows the range of offshore wave period to amplitude ratios of the reviewed 92 studies. The data of Chen and Li (2018), Sumer et al. (1992), Sumer et al. (2001a) are 93 relevant to wind waves ($T \leq \approx 300$ s at full scale, Brown 2013). McGovern et al. (2014) 94 and some of Sumer et al. (1992) are relevant to tides ($T \approx 12-24$ hrs, at full scale). The 95 tsunami-specific studies of Tonkin et al. (2003), Nakamura et al. (2008) and the shortest 96 period used in the current study lie in the period range of 'short tsunami' ($T \leq \approx 180$ s). 97 Few data exist in the 'long tsunami' region ($T \ge \approx 180$ s). The subdivision of 'short' and 98 'long' tsunami is proposed on analysis of Figure 10 in McGovern et al. (2018), in which the 99 runup of long waves normalised by amplitude is plotted as a function of T. A distinct change 100 in the shoaling behaviour of the waves is observed at $T \approx 100$ s, in which waves longer than 101 this value do not appear to shoal significantly. That is, the 'Relative Slope Length' is so 102 large that the incoming wave effectively sees the slope as vertical. The recorded period of 103 the IOT ($T \approx 840$ s, the 'Mercator' profile, Rabinovich and Thomson 2007) and TET ($T \approx$ 104 1260 s), are both within the 'long' tsunami range and would have caused inundation periods 105 that far exceed those generated at model scale by Tonkin et al. (2003) and Nakamura et al. 106 (2008).107



Figure 2: a) KC number regimes and b) the range of a as a function of T tested in the scour literature. Respectively, circular and square points depict circular and square shaped structures, filled and hollow points depict wet and dry sand at the structure and, large and small points depict onshore and offshore scour scenarios.

As scour is driven by the flow and turbulence field around a structure, it is important 108 to assess its development due to an inundation flow with appropriately modelled $\frac{du}{dh}(t)$ that 109 are specific to tsunami time-scales. To bridge the gap identified in the literature, these 110 experiments investigate the scour development at an onshore square structure subject to 111 cyclic inundation from transient flows of lengths and heights, which when scaled up are 112 comparable to tsunami length inundation periods and amplitudes. First the experimental 113 setup is presented. Next, the offshore and onshore hydrodynamics are described. Following 114 this the scour development is described and compared to available scour prediction equations 115 in existing tsunami codes and in the literature for steady currents and waves. A comparison 116 of the scour data is then made with available data in the literature. Finally, a discussion of the 117 limitations of the data is presented together with overall conclusions and recommendations 118 for further work. 119

¹²⁰ 2. Experimental Setup

Cyclic inundation around model onshore buildings is produced using 1:50 Froude scaled crest and trough-led offshore waveforms generated by a Pneumatic Long Wave Generator

(PLWG), as described in Rossetto et al. (2011) and McGovern et al. (2018). Such waveforms 123 are analogous to full-scale tsunami in length and time scales. The PLWG, which in the 124 current set-up is a 4 m high, 3 m wide and 4 m long machined steel box, is placed at the far 125 end of the 75 m long, 4 m wide and 2.5 m deep 'Fast Flow Facility' flume at HR Wallingford, 126 U.K. Generated waves propagate along 23.9 m of constant depth followed by 20 m of 1:20 127 sloping bathymetry, before impinging and inundating on a 3 m long horizontal sediment 128 pit. This sediment pit is divided into three parallel bays by wooden bay splitters (Figure 129 3a-b). Interference from these bay splitters is minimised by using streamline tapers on the 130 leading edge. In the outer bays, a 0.2 m wide square perspex cylinder is placed normal to the 131 incident flow with the leading face 1 m downstream from the leading edge of the sediment 132 pit. These are termed 'Structure 1' (bay 1) and 'Structure 2' (bay 3) within this paper. 133 These represent 10 m x 10 m buildings at prototype scale, located 50 m from the shoreline. 134 Bay 2 contains a 0.4 m wide by 0.2 m long structure, the data of which is not reported here. 135 Due to the relatively low flow velocity in the reported tests, no interference in the overall 136 wave propagation over the test bed is observed due to the presence of the wider structure in 137 Bay 2. A fine, narrow graded sand ($d_{50} = 1.6 X 10^{-4}$ m, where d_{50} is the particle diameter 138 representing the 50% cumulative percentile within a sample of sand) of depth 0.8 m is used 139 in the pit and levelled flat before each test. Due to the low inundation depths associated 140 with the tsunami wave, the tests are relatively less sensitive to variations in particle size 141 than tests undertaken in deeper water as the critical threshold of motion varies slowly in 142 shallow water (e.g. at 0.1 m depth the variation in threshold between 0.1 - 0.7 mm sand 143 is < 20%, see Soulsby and Whitehouse 1997). Therefore, this sediment can be considered 144 representative of a fine-to-medium sand. A rectilinear coordinate system is used with X =145 0 m being the centre of the structure (1.1 m from the sea-ward edge of the sediment pit) 146 and negative towards the PLWG, Z being the vertical coordinate (0 m at the sand surface, 147 negative downwards) and Y being the lateral coordinate (set to 0 m at the centreline of each 148 structure in each bay, and negative towards the right from the perspective of the incoming 149 wave and towards the windows, Figure 3b-c). 150

Scour depth is measured using front-facing GoPro cameras inside each structure. GoPro video is collected at 25 frames-per-second and analysed frame-by-frame to extract sand elevations during tsunami inundation. This is used to determine the rate and depth of scour. The scour depth around the edge of the structure, $d_{sc}(X, Y, Z, t)$, is defined as the location of the sediment-fluid interface. The sediment-fluid interface is distinguished by eye from a



Figure 3: a) cross-sectional schematic of the flume with the onshore [1], near-shore [2] and offshore (constantdepth) [3] regions shown, b) top view of sediment pit region, c) the coordinate system used annotated on a digital picture of the flume test section. All dimensions are in metres (not to scale).

visible change in colour, on individual still frames of the GoPro video (for example, Figure 156 4). These data points are defined in the X and Y planes against a 0.01 m scale grid drawn 157 onto the front and side faces of each structure. This allows d_{sc} to be recorded at 0.01 m 158 intervals along the Y and X planes for the front and side of the structure respectively. The 159 Z grid is scaled to 0.005 m in the X, Y and Z planes. During analysis on a computer, an 160 additional grid is added to the screen to refine the scale to 1 mm, thereby giving an accuracy 161 of ± 0.0005 m in the X, Y and Z directions. Normalising the coordinates by D, $d_{sc}(t)$ is 162 measured on the front faces of the structures (positioned at X = -0.1 m) from Y/D = -0.45163 to Y/D = 0.4 every 0.05D, giving 18 data points. On the right side faces of the structures, 164 (as viewed on Figure 3b, corresponding to Y = -0.1), $d_{sc}(t)$ is recorded every 0.05D from 165 X/D = -0.45 to X/D = 0.45, giving 19 data points. d_{sc} is recorded at a frequency of T/20166 for each wave type (accuracy ± 0.04 s), starting when the wave front first reaches X = -0.1167 m, and continuing for up to 1.5T. Visual analysis is straight-forward when the suspended 168 sediment concentration near the interface is low to medium. However, in periods of vigorous 169 scour, the fluid-sediment interface becomes blurred, leading to an increased uncertainty in 170 the measurement. This will be discussed further in Section 3.2. 171



Figure 4: Example of a raw GoPro video frame on the leading face of the structure with the 0.01 m X grid and 0.005 m Y grid. An additional 0.001 m grid is individually added to the screen during manual processing.

Time-dependent free-surface elevation along the flume $\eta(X, t)$ is recorded using resistancetype wave gauges (accuracy ± 0.0005 m, manufactured by HR Wallingford). These are placed at 5 m intervals from X = -38.64 m to -13.64 m and then at -2.54 m. Eight wave gauges are placed at various locations in the sediment pit, dependent on the individual test. Flow velocities are measured at X = -21.1 m using a Nortek HR Aquadopp and over the sediment pit using two Nortek Vectrino II profilers. The Aquadopp face is 0.06 m from the fixed concrete bed and faces upwards. Velocity profiles are recorded at 1 Hz and are extended to the surface and bed using an exponential fit. Velocities are depth-averaged to produce a time series. The Nortek Vectrino II profilers record velocities at 25 Hz in the X, Y, and Z directions. A Reynolds decomposition gives the mean velocity components.

The sediment pit walls are porous meaning these tests are in the wet regime. The water 182 level is constantly set to the lip of the pit throughout the test campaign preventing any 183 desaturation. It is noted that the wet regime may not always occur in the prototype during 184 the first inundation of a tsunami, but may be applicable to subsequent waves. The potentially 185 increased relative scour of a wet model due to the higher pore-water pressure in comparison 186 to a dry prototype will lead to conservative results. Before each test run, the saturated 187 sand is flattened and the GoPro cameras inserted with WiFi control enabled, allowing single 188 synchronous remote control. The PLWG is switched on and after a short period of settling 189 time, the test is conducted and the scour, velocity and η are recorded. 190

The test conditions as recorded at X = -1.1 m (X/D = -5.5) are given in Table 1. This position corresponds to the upstream lip of the sediment pit. The origin of the parameter values are described in Section 2.2. Before this in Section 2.1, the characteristics of the offshore waveforms that propagate over the sloping bathymetry before inundating over the sediment pit are described.

196 2.1. The offshore waveform

The offshore waveforms generated include crest-led waves of T = 25 s (CL25) and 147 s 197 (CL147) and a trough-led wave of T = 49 s (TL49). Tsunami have been observed to exhibit 198 both crest-led and trough-led shapes, for example see Tadepalli and Synolakis (1994) and 199 Madsen et al. (2008). Figure 5a-c shows free surface elevation η at X/D = -23.64 m as a 200 function of t (where, t = 0 is the start of the PLWG wave generation cycle, which includes 201 60 s of still water before the wave begins) for the CL147a, TL49a and CL20a tests. Each are 202 typical of the relevant wave periods. From Figure 5a-c, the periods of each wave are defined 203 as $T = t_{end} - t_{start}$ where t_{start} and t_{end} are defined as the times at which $\eta(X, t)$ first up-cross 204 and down-cross the value corresponding to 1% of a respectively (see also McGovern et al. 205 2018). X = -23.64 m is the wave gauge in the offshore region nearest to the bathymetry toe, 206 and represents the position at which the waveforms are calibrated. This position is chosen as 207

it represents a location where reflections from the slope are manifest almost instantaneously on the waveform, and it constitutes a definitive change in slope that is easier to define in a prototype. Due to the very long wavelengths of the waves being produced, their recording at any given point in the flume may be a composite of the incident and reflected components, the main source of the reflection being the sloping bathymetry. The definition point is discussed in detail in McGovern et al. (2018), who also show that the PLWG effectively absorbs reflections from the slope.

The crest-led waves produced by the PLWG are much longer than the theoretical solitary waveform given by Equation 1. Clearly, the short inundation time that occurs from a solitary wave will not result in the long period scour regime that would be expected for a tsunami-like inundation. The trough-led wave is plotted against the theoretical *N*-wave (Equation 2) and the sine function $\eta(t) = a^+ \sin(2\pi f t)$, where *f* is frequency. The measured wave is longer and shallower than the *N*-wave, and more closely matches the sine waveform.

$$\eta(X,0) = \frac{H}{d}\operatorname{sech}^2(K_s(X-X_1))$$
(1)

where $K_s = 1/d\sqrt{3H/4d}$, and H = wave height.

$$\eta(X,0) = \alpha \frac{H}{d} (X - X_2) \operatorname{sech}^2(K_s(X - X_1))$$
(2)

where α is a constant, X_1 is the position the crest and X_2 is the horizontal position of the zero-crossing point in the wave profile.



Figure 5: a-c measured $\eta(X)$ as a function of t for the CL147, TL49 and CL25 waves respectively. The CL waves are compared against the theoretical solitary waveform, while the TL49 wave is compared against the theoretical N-wave and sine function.

The Aquadopp velocity data recorded at X = -21.1 m is presented in Figure 6a-f, with 224 a), c) and e) showing the streamwise u velocity profile as a function of t/T and b), d) 225 and t) the depth-averaged velocity \overline{U} and free-surface η for the CL147a, TL49a and CL25a 226 waves respectively. At X = -21.1 m the velocity profiles are 2-dimensional, with minimal \overline{V} 227 component. The occurrence of maximum velocity, \bar{U}_{max} and maximum free surface, η_{max} , 228 are out of phase. \bar{U}_{max} occurs at $\approx \frac{2}{3}$ of η_{max} , at which point $\frac{d(\eta)}{d(t)}$ is also approximately at its 229 maximum. This corroborates the time at which inferred overland maximum velocities occur 230 from video analysis of the TET as used in the ASCE (2016) design standard (Figure 6.8-1 231 therein) to calculate the onshore tsunami flow velocity at a given inundation height. The 232 velocity-height data presented here provides experimental confirmation of this relationship. 233 The phase difference between \overline{U} and η means that towards the end of the wave, \overline{U} becomes 234 negative, representing a return flow. 235



Figure 6: a-f. Aquadopp velocity data recorded at X = -21.1 m where a), c), e) shows the *u* velocity profile as a function of t/T for the CL147a, TL49a and CL25a respectively and b), d), f), the depth-averaged velocity \bar{U} , and free surface height η [m] as a function of t/T, for the CL147a, TL49a and CL25a respectively. The noise at ≈ 0.9 m above the bed after $t/T \approx 1.25$ on a) is due to the water surface.

236 2.2. The onshore inundation characteristics

The offshore waveforms described above propagate over the sloping bathymetry before 237 impinging on the test bed and structure. This inundating flow velocity and height are not 238 equal to the offshore values. Table 1, therefore, gives the onshore values at the position 239 X = -1.1 m as these values are more useful in relating to the onshore scour. The value of 240 \overline{U}_{max} in Table 1 is the maximum onshore value extracted from the Vectrino profilers. The 241 Vectrino's record the bottom 0.035 m of the flow depth which means that the U_{max} given is 242 likely to be lower than \overline{U}_{max} averaged over the whole flow depth. This value is used in the 243 KC calculation instead of the offshore value recorded by the Aquadopp as the flow velocity 244 significantly increases onshore, and the appropriate KC number relating to the scour at the 245 structure is that calculated from the parameters nearest the structure. For tests CL147b 246 and CL147c the Vectrino is moved to a near-structure location, so there is no value for U_{max} 247 at X = -1.1 m. However, it is assumed that as the offshore waveform is the same, the 248 onshore flow is likely similar. Therefore, the values of Reynolds Number $R_h = \frac{\rho \bar{U}_{max} h_{max}}{\mu}$, 249 (where h_{max} is the maximum onshore inundation height, ρ the density of water = 1000 kg 250 m³ and μ is the dynamic viscosity of water = 1.307 ×10⁻³), Froude Number $Fr = \frac{\bar{U}_{max}}{\sqrt{gh_{max}}}$ 251 and KC from CL147a are assumed to represent CL147b-c as well. The Shields parameter is 252 calculated using the expressions provided in Fuhrman et al. (2013), reproduced in Equation 253 3. 254

$$\theta = \frac{U_{fm}^2}{(s-1)gd_{50}} \tag{3}$$

where U_{fm} is given by

$$U_{fm} = \sqrt{\frac{f_w}{2}} U_{max} \tag{4}$$

where f_w is the friction factor. Hydraulically smooth conditions prevail in the CL147, TL49 and CL25 waves as $ks^+ = (ks U_{fm})/\nu$ does not exceed 10, where ks is the Nikuradse roughness equivalent for the sand used, and ν is the kinematic viscosity of water. Thus f_w is given by Fuhrman et al. (2013) as

$$f_w = 0.04 R e^{-0.16} \tag{5}$$

and is shown to be a reasonable estimate for use with tsunami by Williams and Fuhrman 261 (2016). Here, $Re = \frac{aU_{max}}{\nu}$, where $a = \frac{U_{max}T}{2\pi}$. For hydraulically rough conditions Williams and Fuhrman (2016) suggest Equation 6.

$$f_w = exp\left(5.5\left(\frac{a}{ks}\right)^{-0.16} - 6.7\right) \tag{6}$$

This method is also employed by Larsen et al. (2018) for their offshore tsunami cases. Table 1 provides the Shields parameter $\theta_{onshore}$ as calculated at X = -1.1 m, i.e., the value in the vicinity of the structure. The critical Shields parameter for incipient sediment motion $\theta_{cr} = 0.055$ is given by the method outlined in Soulsby and Whitehouse (1997), Equation 7.

$$\theta_{cr} = \frac{0.3}{1 + 1.2d_*} + 0.055(1 - exp(-0.020d_*)) \tag{7}$$

where dimensionless grain size d_* is given by Equation 8.

$$d_* = \left[\frac{g(s-1)}{\nu^2}\right]^{\frac{1}{3}} d_{50} \tag{8}$$

Additionally on Table 1 the number of front (small 'f') and side (small 's') scour depth data sets recorded is given. In some tests, GoPro failures prevented the collection of usable scour data.

Table 1: Key wave parameters at X = -1.1 m and the number of scour data sets obtained

Run	T [s]	$\bar{U} \text{ [m s}^{-1}\text{]}$	maximum	R_h	Fr	KC	$\theta_{onshore}$	$\frac{\theta}{\theta_{cr}}$	scour
			h [m]						data sets
CL25a	25	0.666	0.207	1.05×10^{5}	0.47	83	0.8	12.7	2f, 1s
CL25b	25	0.666	0.208	$1.06\! imes\!10^5$	0.47	83	0.8	12.7	2f, 1s
TL49a	49	0.324	0.121	2.99×10^{4}	0.30	79	0.16	2.48	2f, 1s
TL49b	49	0.334	0.119	3.04×10^4	0.31	82	0.17	2.62	2f, 1s
CL147a	147	0.382	0.093	2.72×10^4	0.40	281	0.22	3.50	1f, 2s
CL147b	147	-	0.09	2.63×10^4	0.41	281	0.22	3.51	1f, 1s
CL147c	147	-	0.093	2.72×10^4	0.40	281	0.22	3.5	1f, 1s

From Table 1, the equivalent full-scale sediment grain size is 9.7 mm for the CL25 wave condition, when similitude in flow intensity U/U_c is attained between the model and prototype. For all waves, the prototype Reynolds numbers are 2 orders of magnitude larger leading to turbulent wake formation in both the model and prototype.

275 3. Results

276 3.1. Flow Characteristics around an Onshore Structure

Scour is caused by the change in the free-stream flow field by the presence of a structure. 277 In unidirectional currents and waves, this flow structure is relatively well defined. It is a 278 reasonable hypothesis to assume that the instantaneous flow field around a structure during 279 tsunami inundation is analogous to that of a steady current, and similar arguments are made 280 for tidal flows at offshore structures (e.g., Whitehouse 1998 and McGovern et al. 2014). The 281 caveat is that this would only apply to boundary layers that extend over the entirety of the 282 flow depth, as Williams and Fuhrman (2016) and Larsen et al. (2018) show the tsunami 283 boundary layer may also exhibit wave-like characteristics. This section discusses the onshore 284 flow characteristics in an attempt to verify this hypothesis. In this section all X, Y and Z285 positions are normalised by D. Instantaneous time t is normalised by period T, where t/T286 = 0 denotes the time at which the wave start is recorded at the respective position. 287

Figure 7a shows streamwise \overline{U} , lateral \overline{V} and vertical \overline{W} onshore velocities at onshore 288 locations in Bay 3 around Structure 2, where X/D = -5.5, taken by a single Vectrino II 289 profiler during test CL147a. Figure 7b shows the same onshore velocities at X/D = -1.1290 and -1.175 taken simultaneously by a pair of Vectrino II profiles during test CL147b (see 291 legend for full coordinates). The onshore water depth h(t) recorded at X/D = -5.5, Y/D292 = 0 (the centreline) for the CL147a and CL147b wave runs is also given in Figure 7a-b, 293 respectively. There is good agreement between experimental runs in h(t). The delay in the 294 velocity record compared to h(t) is due to the flow depth being below the Vectrino transducer 295 head. Vectrinos are advantageous for boundary layer measurements over counterparts that 296 may be deployed, due to their low profile and ability to provide non-invasive measurements 297 beyond the effects of the probe head (defined by the blanking distance). Additionally, they 298 are able to measure a flow profile from which the depth-averaged velocity may be derived. 299 It should be noted that the profiler transducer head begins each experiment exposed to air 300 before being submerged. Readings only occur for $h \geq$ transducer head height. 301

h at X/D = -5.5 is lower $(h_{max} \approx 0.093 \text{ m})$ than at X/D = -118.2 (i.e., X = -23.64m, where $h_{max} \approx 0.11$ m, see Figure 6b) due likely to the acceleration of the flow over the onshore region indicating a transition from wave to current-like flow. \bar{U} at X/D = -5.5(Figure 7a) decreases with time from a peak of 0.38 m/s corresponding to $\approx \frac{2}{3}h_{max}$, again in agreement with Figure 6b and ASCE (2016). This scales up to ≈ 2.7 m/s at 1:50. Field measurements of tsunami overland velocities have been shown to be in the region of 2 - 5 m/s (Fritz et al., 2006). On Figure 7b $\bar{U}_{max} \approx 0.4$ m/s is recorded at X/D = -1.1, Y/D = -0.5 (in

line with the corner of the structure), due to flow constriction along with significant negative 309 \overline{V} (describing flow to the right of the incident wave direction, towards the flume wall, Figure 310 3b), due to the deflection of incoming flow across the front face of the structure. It should 311 be noted that unlike elsewhere in the monitored onshore and nearshore regions, $U_{max} \approx 0.4$ 312 m/s at the leading corner of the structure (X/D = -1.1, Y/D = -0.5) occurs in-phase with 313 h_{max} . This observation appears to contradict the guidelines in ASCE (2016). At X/D = 314 -1.175, Y/D = 0, \overline{U} reaches a maximum at $\approx \frac{2}{3}h_{max}$ as seen in Figure 7a, but reduces in a 315 more non-linear manner in the latter stages of the inundation. The variation indicates the 316 relatively turbulent nature of the flow in this region which is due to the presence of a growing 317 scour hole affecting the flow near and at the bed. \overline{V} is zero as expected at the centreline, 318 and \overline{W} is slightly negative due to the presence of the downflow closer towards the structure. 319



Figure 7: a) h (m, left y axis), \overline{U} , \overline{V} and \overline{W} (m/s, right y axis) as a function of t/T at X/D = -5.5, Y/D = 0 during CL147a, and b) during CL147b at X/D = -1.175, Y/D = -0.5, and X/D = -1.1, Y/D = 0.

The equivalent \overline{U} , \overline{V} and \overline{W} as a function of t/T for the TL49 and CL25 waves is not available due to a failure of the synchronisation signal between the wave gauge data acquisition and the Vectrinos. While time series velocity data exists it cannot be matched with the time series wave gauge data with certainty. However, the maximum values can be reported (Table 1).

325 3.2. Tsunami Induced Onshore Scour

The time development of scour is now discussed beginning with the CL147 wave which is repeated three times (CL147a, b and c, see Table 1). There is good agreement in the following discussion of the recorded scour process from the side and front views of the structures for all wave runs. Hence for brevity, the detailed process of scour is discussed only in relation to Structure 1 and CL147a.

Figure 8a-j shows video image stills of the scour development at the front and side of the structure at selected instances of the inundation. Here, t/T = 0 denotes the time at which the wave front first impinges on the structure. The estimated duration and delineation of flow direction in the inundation process is made from examining individual video frames. Flow direction is onshore between t/T = 0 - 0.845 after which flow reversal occurs.



Figure 8: GoPro video stills from inside Structure 1 at variable intervals from the start of inundation during CL147a selected to highlight the scour process. The left and right columns show progressively $t/T \approx 0.125$, 0.25, 0.5, 0.8 and 0.875 for the side and front views respectively. Refer to the text for explanations of the annotations.

Figure 9a-b shows the time development of scour along the side face and front face 336 respectively during the inundation process for Structure 1 during CL147a. The scour depth 337 d_{sc} is plotted at 6 s intervals (t/T = 0.043) from t/T = 0 and as a function of X/D for 338 the side face (Figure 9a) and Y/D for the front face (Figure 9b). The minor offset of the 339 initial bed level from zero observed in Figure 9a-b at t/T = 0 is within experimental error 340 and no obvious bias in the scour depth appears to be carried forward into the later stages of 341 scour development. Bed levels can only be extracted at the sediment-water interface when 342 there is a strong contrast in light and dark between the water and the sediment. During the 343 experiment instantaneous changes in the lighting and reflection during the scour development 344 lead to losses in data. The region between X/D -0.45 to -0.5 and 0.45 to 0.5 on Figure 9a 345 and between $Y/D \approx -0.5$ to -0.45 on Figure 9b contain no data as light refraction from the 346 side panel of the perspex structure distorts the GoPro image preventing the distinct contrast 347 between sand level and water column. There is no data between $Y/D \approx 0.4$ to 0.5 for similar 348 reasons. Additionally, as sharpness of the fluid-sediment interface varies depending on the 349 instantaneous conditions of the flow and suspended sediment concentration, the error in d_{sc} 350 recorded at any position varies through the inundation. This error increases from $t/T \approx$ 351 0.2 to $t/T \approx 0.5$, when depth-averaged flow velocity U is relatively high (Figure 7), and the 352 vigorousness of scour is greatest (for example, Figure 8e and f). The scour analysis in this 353 paper focuses on the maximum scour depth, $d_{sc,max}$, which occurs in the region 0.55 < t/T354 <0.80; and the final scour depth, $d_{sc,end}$, that occurs at t/T > 1. $d_{sc,end}$ is the end scour 355 depth recorded as the mean value after the change in d_{sc} becomes less than 1% of the current 356 value. During these times U is reduced and suspended sediment load is decreased, meaning 357 the sediment fluid boundary is distinct, giving an accuracy $d_{sc} \pm 0.001$ m, (less than <1%358 of the maximum d_{sc}). 359



Figure 9: a-b. The development of scour at the side a), and front faces b) of Structure 1 CL147a wave. Bed level readings are taken every 6 s (t/T = 0.04). The time at which $d_{sc,max}$ and $d_{sc,end}$ are achieved is highlighted. The small variation of the initial bed level around zero does not appear to have any significant impact on the scour development, which is qualitatively similar to the CL25 and TL49 tests (see Figures 11a-d) maxima and end depths.

The following discussion refers to both Figures 8a-j and 9a-b. The scour initiates at 360 the corner of the structure, gradually moving towards the centreline where scour initiates \approx 361 40 s later (t/T = 0.27). On the front face the scour hole forms, and retains until the end 362 of the test, a triangular shape with the apex located on the centreline. This is indicative 363 of the early stages of scour development at a square structure (for example, Sumer et al. 364 1993). Along the side face scour also begins at the corner moving gradually downstream 365 along the structures edge (in agreement with Nakamura et al. 2008 and Shafiei et al. 2015). 366 The largest scour depth is observed at the corner and is due to a strong vortex generated 367 by lateral boundary layer separation from the structures edge. This vortex is observable in 368 the videos and in Figure 8c-f in particular (see annotations). In studies of air-flow past a 369 square cylinder, this type of vortex has been termed a base-vortex (for example Saha 2013). 370 From the observation of the videos, impinging water on the front face is deflected down 371 and away from the centreline following the triangular shape of the scour hole. The general 372 behaviour of the scour process is most readily apparent in Figures 8e-f. The process appears 373

to be primarily dominated by the lateral vortex energetically removing sediment from the 374 corner. The movement of sediment through the scouring region can be grouped into three 375 observed behaviours. These are illustrated by three sets of red arrows in Figure 8e-f which 376 indicate the observed movement of sediment. Additionally, these features are represented 377 schematically on Figure 10a-b. Movement of sediment towards the corner of the structure is 378 observed from upstream of the leading lip of the scour hole, the sides of the scour hole and 379 from the centreline apex, which in three-dimensions is a ridge (Figure 8f arrows [1]). This 380 sediment is then suspended by the lateral vortex and carried downstream by the prevailing 381 flow past the structure [3]. [1] is bounded by a distinct region that is farther away from 382 the centreline where sediment is suspended via a different process to the lateral vortex and 383 carried laterally outwards and then downstream [2]. This may be elements of a horseshoe 384 vortex forming from the separation of the upstream bed boundary layer at the lip of the 385 upstream scour hole. 386



Figure 10: Schematic representations of the scour process as depicted in Figure 8e-f at t/T = 0.5 from the a), top down and b), side views respectively.

As shown by Hjorth (1975), the leading corner is the position of greatest bed shear 387 stress amplification, while the centreline exhibits bed shear amplification ≈ 1 . This would 388 explain the delay in scour along the centreline. This delay indicates that the horseshoe 389 vortex is not likely to be a strong influence on the early stages of the scour process, as if 390 it were, the observed delay would be much less. At wetted circular structures, the scour 391 process also begins laterally before quickly migrating towards the front as the downflow and 392 horseshoe vortex establish themselves as the dominant mechanism (for example, Ettema 393 1980, Melville and Coleman 2000). The horseshoe vortex may participate more in the later 394 stages of inundation, though the lack of suspended sediment observed in the front face 395

throughout Figure 8 suggests that it remains a secondary scouring phenomena, and forms further upstream of the structure from the separation over the scour hole upstream lip. For the duration of a single inundation as generated here, the scour mechanism appears to be dominated by the lateral vortex.

 $d_{sc,max} = 0.12$ and 0.104 m occurs at t/T = 0.6 and 0.68 on the side and front faces 400 respectively. Once $d_{sc,max}$ is achieved, backfilling occurs at the corners due to sediment 401 slumping. In Figure 9a the majority of the slumping occurs between X/D = -0.45 to -0.25402 on the side face and Y/D = -0.45 to -0.1 on the front face. The maximum slope angles of the 403 bed observed on the side and front faces when $d_{sc,max}$ occurs is 84.3° and 81.4°, respectively. 404 The majority of the slumping along the side face occurs between t/T = 0.69 - 0.81 due 405 presumably to the flow velocity dropping below the velocity threshold required to maintain 406 a steeper slope. The natural angle of repose of the sediment is 31°. Beyond these regions 407 $d_{sc,max} \approx d_{sc,end}$, suggesting that the slumping sediment originates from the sides of the scour 408 hole collapsing in towards the structure. Along the front face a 0.031 m decrease in depth 409 occurs between $\approx t/T = 0.68$ - 0.82. The slight delay in slumping at the side wall may be 410 due to the lateral vortex retaining its identity slightly longer than the scouring phenomena 411 at the front face (horseshoe vortex and downflow), due to the sharp separation edge provided 412 by the structures' corner. This can be observed in Figures 8g-h which shows some suspended 413 sediment and a vortical structure at the side face at t/T = 0.8. While no onshore velocity 414 record is available at this point due to the reduction of h below the Vectrino transducer 415 heads, an inference can be made from the offshore velocity. Figure 6b shows that offshore 416 velocities will approach zero and reverse after t/T = 0.75 ($\approx \frac{3}{4}T$), thus the period between 417 t/T = 0.68 - 0.85 onshore can be assumed to coincide with the occurrence of velocities 418 approaching zero. This is further corroborated by visual analysis of the GoPro videos, with 419 Figure 8h displaying a major slumping event at the front face at t/T = 0.8 occurring with 420 low suspended sediment indicating lower flow velocities (as also observed during playback). 421 This image and playback shows that the slumping of sediment occurs from the sides of the 422 scour hole slumping in towards the structure as well as along the structures' surface. The 423 slumping is staggered in time with a second event backfilling the region between the corner 424 and centreline at approximately t/T = 0.8 - 0.86, (Figures 8j and 9b). 425

Figure 8i-j, taken at t/T = 0.875 during the return flow shows significant suspended sediment in what is now the rear of the structure relative to the flow direction. This implies that the scour process is now reversed. Hence, the four distinct sediment transport phases that appear to occur during the inundation process may be identified as: 1) initial local scour during inundation, 2) backfilling from maximum scour depths during inundation and flow reversal, 3) local scour due to the return flow and, 4) backfilling towards and beyond the end of the return flow.

Figure 11a-d shows the scour time development for the side (a and c) and front (b and 433 d) of the structure during the TL49a and CL25a waves respectively. Similar to the CL147a 434 wave, scour begins at the corners. At the front, the scour develops in much the same way 435 with a triangular bed level with the apex at the centreline, and significant slumping occurs 436 towards the end of the waves. The side views have a similar shape with the deepest scour 437 depth occurring at X/D = -0.45. Slumping, however, is much smaller than observed for the 438 CL147a wave. The scour process appears much the same as for the CL147a wave, however, 439 the horseshoe vortex, which rotates clockwise, is more apparent particularly in the early 440 stages of these waves (see Appendix A, Figures A.1 and A.2). 441



Figure 11: a-d. The development of scour at the side (Figure 11a, c), and front faces (Figure 11b, d) of the structure during the TL49a (top row) and CL25a (bottom row) waves. Bed level readings are taken every 1 s (t/T = 0.023) and 0.5 s (t/T = 0.02) for the TL49 and CL25 waves respectively. The time at which $d_{sc,max}$ and $d_{sc,end}$ are achieved is highlighted.

Further discussion on the role of the horseshoe vortex can be made by comparing the 442 observed process of scour with published literature. Tonkin et al. (2003) cases I and II for un-443 submerged and partially submerged cylinders in sand, respectively, show the horseshoe vortex 444 to be a significant scouring phenomena in the early stages of solitary wave inundation. Its 445 formation is from the downward flow momentum caused by the plunging breaker just before 446 the cylinder. Lavictoire (2014) also observe the horseshoe vortex to be present during bore 447 impacts with the structure. In the current tests, the CL25 waves have already broken, and 448 impact the structure led by a small broken front. The TL49 and CL147 waves do not break, 449 and do not exhibit a discernible broken wave front upon impact. It seems, therefore, that in 450 the current tests the horseshoe vortex is less important in the scour process, particularly for 451 the CL147 waves. 452

453 3.3. Time Development and Equilibrium

The recorded time development of scour is now discussed. For all waves live-bed conditions prevail with $\theta > \theta_{cr}$. While velocity data is not available throughout the entire inundation process, video and visual observations during the tests reveal that rippling of the bed starts immediately after inundation begins for all waves. Despite the prevalence of live-bed conditions, it does not appear that equilibrium is achieved in any test, due to the triangular scour hole shape.

Figure 12a-b shows $d_{sc,max}$ versus $d_{sc,end}$ at the side face and front face for all tests and structures, respectively. In all waves and locations $d_{sc,max} > d_{sc,end}$, in agreement with observations from Nakamura et al. (2008). The raw values are given in Table 2 along with the percentage differences between $d_{sc,max}$ and $d_{sc,end}$ for all waves.

The CL147 waves produce the greatest scour. For this wave KC = 281, indicating that despite the flow velocity being lower than that of the CL25 waves ($\bar{U} = 0.382$ and 0.666 m/s respectively) and comparable to that of TL49 waves (where \bar{U} ranges between 0.324 -0.334 m/s, Table 1), the inundation time (i.e., T) is much longer than both. This means that the scouring flow field has a longer period of time to entrain sediment from the bed and transport downstream.



Figure 12: a-b. $d_{sc,max}$ versus $d_{sc,end}$ at the corner positions of a), the front face (Y/D = -0.45, X/D = -0.5) and b), side face (Y/D = -0.5, X/D = -0.45) of the structures for all tests.

Figure 13 shows the normalised scour depth d_{sc}/D as a function of t/T for CL147a, 470 TL49a and CL25a. These are typical of the repeated runs for each wave period. For CL147a 471 $d_{sc}/D(t)$ along the centreline position follows an exponential scour development curve similar 472 to that observed in unidirectional scour (e.g., Melville and Coleman 2000). The rate at the 473 front corner location on the side face $(X/D = -0.45, Y/D = -0.5, \text{ where } d_{sc,max} \text{ is recorded}),$ 474 however, exhibit non-linearity in the scour process. This is manifest as a less smooth curve in 475 comparison to centreline. The non-linearity is significant at this position due to the presence 476 of the lateral base-vortex. Here, the scour rate decreases until the maximum scour depth 477 $d_{sc,max}/D$ occurs at $t/T \approx 0.57$, after which slumping occurs. (Note, this value of t/T is not 478 equal to that on Figure 9, which only includes measurements at intervals of t/T = 0.04). 479 The centreline curve indicates the fastest rate of scour occurs at $t/T \approx 0.5$, coinciding with 480 h_{max} . 481



Figure 13: Centreline and side face corner scour time development curves for the CL147a, TL49a and CL25a wave runs at Structure 1.

For the TL49a wave run, the scour development is relatively more irregular that for the 482 CL147a at all positions. This is likely a due to the shorter and more turbulent nature of 483 the inundation. The majority of the scouring occurs in the 1st third of the inundation. 484 $d_{sc,max}/D$ occurs earlier in the inundation time in comparison to the CL147a wave above, at 485 $\approx t/T = 0.33$, after which a small amount of slumping occurs again. Scour at the centreline 486 is minimal, reaching a maximum of 0.03D and no slumping is observed. $d_{sc}/D(t)$ for the 487 CL25a wave reaches a maximum at $\approx t/T = 0.48$ and slumping occurs immediately after. 488 As with all other waves, the corner scour is much greater than the centreline. No slumping 489 occurs at the centreline and $d_{sc,max}/D$ is limited to 0.05D. 490

It is uncertain whether equilibrium can be attained during single tsunami wave inunda-491 tion. Progress to equilibrium will primarily be driven by the tsunami duration to time scale 492 of scour ratio, which for a single tsunami inundation will likely be low. The equilibrium 493 depth for a given onshore structure may, therefore, only be achieved after several inundation 494 and return flows such as during a tsunami wave train event. Larsen et al. (2018) observed 495 equilibrium in their offshore tsunami cases was achieved only after approximately 50 waves, 496 suggesting that it may take numerous waves to achieve equilibrium onshore as well. Knowl-497 edge of the inundation and return flow durations can be used to estimate whether equilibrium 498 will be achieved in a given tsunami event. In such cases where a small number of tsunami 499

waves inundate onshore in one tsunami event, scour may be better characterised by the spatial and temporal location of $d_{sc,max}$, the change in d_{sc} around the structure (which may influence the structure dynamic response to hydrostatic and hydrodynamic loading) and $d_{sc,end}$.

⁵⁰⁴ 3.4. Comparison of Results with Prediction Equations

Recorded $d_{sc,max}$ for each test and structure is here compared to well-known empirical equilibrium scour depth (d_{sce}) predictor equations. The comparison is made with the caveat that such equations are developed for either waves, or currents only, and for the case of offshore / fully wetted scenarios.

For waves, currents and combined wave and currents, d_{sce} is equivalent to $d_{sc,end}$ which is defined when, for example, the depth of scour increases by less than 5% in 24 hours (Melville 1997). d_{sce} is generally equal or similar to $d_{sc,max}$. However, $d_{sc,max}$ in live-bed conditions, tidal flows and waves is not necessarily equal to d_{sce} . In such scenarios the periodic passing of ripples through the scour hole and/or changes in flow direction may cause $d_{sc,max}$ to vary by a small amount around the mean value given by d_{sce} . For the purposes of the comparison below, $d_{sc,max}$ is assumed to equal d_{sce} .

The Colorado State University equation (CSU, Equation 9) as cited in the HEC-18 Evaluating scour at bridges (Richardson and Davis, 2001) commissioned by the US Federal Highway Administration is widely used to calculate the equivalent $d_{sc,max}$ for cylindrical structures in a unidirectional steady current scenario.

$$\frac{d_{sc,max}}{D} = 2K_1 K_2 K_3 K_4 \left(\frac{h}{D}\right)^{0.35} F_r^{0.43} \tag{9}$$

where $K_1 = \text{correction factor for pier shape (1.1 for square nosed)}, K_2 = \text{correction factor}$ for angle of attack of flow (1 for 0°), $K_3 = \text{correction factor for bed condition (1.1 for small}$ $dunes / plane bed), <math>K_4 = \text{correction factor for bed armouring (1 for narrow graded sand)}.$ Correction factor values are determined from Tables 6.1-6.3 in Richardson and Davis (2001). For the present tests, the flow parameters are derived at X/D = -5.5.

For $d_{sc,max}$ in waves, the influence of KC number is illustrated in Figure 11 of Sumer et al. (1992) which shows d_{sc}/D as a function of KC. Sumer et al. (1992) show that for KCapproximately > 10², d_{sc}/D approaches an asymptote of 1.3, as given by Equation 10.

⁵²⁹
$$\frac{d_{sc,max}}{D} = 1.3(1 - exp(-0.03(KC - 6))), \text{ for } KC > 6 \tag{10}$$

Sumer et al. (1993) conducted experiments to investigate the effect of cross-section on scour as a function of KC. They determined the empirical expression show in Equation 11 for $d_{sc,max}/D$ for a square structure oriented 90° to the incident wave in live-bed conditions. Such a scenario is the most relevant to the current tests.

534

$$\frac{d_{sc,max}}{D} = 2(1 - exp(-0.015(KC - 11))), \text{ for } KC > 11$$
(11)

The (ASCE, 2016) Tsunami Loads and Effects design codes present a simple empirical prediction model for onshore tsunami induced scour. This is based on post tsunami field surveys of scour holes around structures (see Tonkin et al. 2013). An envelope of scour depth is provided based on the inundation height h. This is $d_{sc,max} = 1.2h$ for h < 3.05 m and $d_{sc,max} = 3.66$ m for h > 3.05 m. The (ASCE, 2016) predictions are included in Table 2. As h in all waves in the model is > 3.05 m at 1:50 scale, the predicted scour depth is therefore 3.66 m which at 1:50 scale is 0.0732 m.

Figure 14 shows $\frac{d_{sc,max}}{D}$ recorded at the side face of the structures as a function of a), 542 T and b), KC. The predicted $\frac{d_{sc,max}}{D}$ from Equations 9, 10, 11 and ASCE (2016) are also 543 plotted. The raw values including $d_{sc,max}$ and $d_{sc,end}$ are given in Table 2 and KC numbers 544 in Table 1. Focussing on the side face which gives the larger scour depths as opposed to 545 the front face, the value of $d_{sc,max}$ for the CL147 waves is less than half that predicted 546 from Equations 9 and 10 (respectively 0.258 m and 0.26 m, Figures 14a and b). $d_{sc,max}$ 547 is over three times less than that predicted by Equation 11 (0.39 m, Figure 14b). Over-548 predictions are present for the TL49 and CL25 waves also. For the TL49 waves, the ASCE 549 (2016) performs well (Figure 14a). For the CL25 and CL147 waves, the ASCE (2016) under 550 predicts $d_{sc,end}$, but only by a relatively small amount (Table 2). However, a critical finding 551 of these experiments is that $d_{sc,max}$ is in some cases up to a third greater than $d_{sc,end}$. Thus 552 the use of the ASCE (2016) prediction, which is based on post-tsunami scour observations 553 of $d_{sc,end}$ may lead to undesirable underestimations of $d_{sc,max}$, which may occur earlier in the 554 inundation. The ASCE (2016) prediction does not account for variables that are known to 555 influence scour, such as flow velocity, KC number, and structure diameter. Based on the 556 current limited data, it is difficult to conclude over which ranges of these parameters, use of 557 the ASCE (2016) will lead to an under-prediction of scour. 558

ASCE	predic-	tion [m]						0.0732						
Sumer et al. (1993)	Equation	11 [m]	0.39	0.39	0.39	0.39	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
Sumer et al. (1992)	Equation	10 [m]	0.26	0.26	0.26	0.26	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
HEC-18	Equation	9 [m]	0.25	0.25	0.25	0.25	0.24	0.24	0.24	0.24	0.35	0.35	0.35	0.35
% reduction	from	$d_{sc,max}$	33	32	32	33	4	ı	9	ı	6	ı	9	ı
X/D = -0.45	$d_{sc,end}$	[m]	0.08	0.08	0.079	0.08	0.067	I	0.068	I	0.075	I	0.075	ı
Side face	$d_{sc,max}$	[m]	0.12	0.117	0.116	0.12	0.07	I	0.072	I	0.082	I	0.08	
% reduction	from	$d_{sc,max}$	ı	24	23	28	17	6	13	12	16	13	25	14
Y/D = -0.45	$d_{sc,end}$	[m]	•	0.076	0.076	0.075	0.058	0.068	0.061	0.06	0.067	0.065	0.071	0.065
Front face	$d_{sc,max}$	[m]	1	0.1	0.099	0.104	0.07	0.071	0.07	0.068	0.08	0.075	0.095	0.076
Struc-	ture		-	2	Ţ	Ţ	-	2	Ţ	2	Ţ	2	-	2
Wave	Run		CL147a	CL147a	CL147b	CL147c	TL49a	TL49a	TL49b	TL49b	CL25a	CL25a	CL25b	CL25h

y the percentage difference between the two is given, along	
and $d_{sc,end}$ values for each wave	max using Equations 9, 10, 11 and
Table 2: All $d_{sc,max}$ a	with the predicted d_{sc}



Figure 14: a), $d_{sc,max}/D$ as a function of T at the side faces of the structures for all waves and, b), $d_{sc,max}/D$ plotted as a function of KC at the side faces of the structures respectively. The appropriate predictor equations are also shown. T_{crest} is the period of the crest of the TL49 waves and is discussed in Section 3.5.

The TL49 and CL25 waves produce similar $d_{sc,max}$ and have similar KC numbers (of 559 79 - 83, Figure 14, also Tables 1 and 2). CL147 has a larger KC (281) and $d_{sc,max}$ than 560 both. The results are in line with the expected influence of KC, however, the values are 561 significantly lower than those expected from Equation 10 and 11. This certainly suggests 562 that equilibrium scour depth is not achieved, and it may also be stipulated that the KC563 number may not be the only appropriate variable for tsunami inundation. Wind wave scour 564 is strongly related to KC as it describes the orbital motion of the fluid which alternates 565 the flow direction during each period, and therefore, the temporal duration and strength of 566 the main scouring phenomena during each period. The orbital motion of the wave is less 567 apparent in tsunami inundation, however. While the inundation is driven by the incoming 568 wave, it is hypothesised that the wave energy is significantly dissipated through bed friction 569 and the overland return flow (though not modelled in these tests) is likely more similar to 570 open channel surface flow governed by gravity. 571

572 3.5. Comparison of Results with Published Experimental Data

⁵⁷³ By comparing the experimental data with appropriate published data, the influence of ⁵⁷⁴ inundation height and duration on the scour depth can be investigated. The experimental

data of Nakamura et al. (2008), Lavictoire (2014) and Shafiei et al. (2015) are the most 575 comparable studies to the current experiments. Nakamura et al. (2008) conducted tests of 576 'long waves' and solitary waves. These over-topped a sea wall to scour at an onshore square 577 structure, and as such are the most similar to the current tests. The maximum period tested 578 was 14 s. Lavictoire (2014) studied the inundation of bores with a circular structure in sand 579 and gravel beds. Shafiei et al. (2015) observed bore inundation and scour around square, 580 diamond and circular structures in sand beds, focussing on the effect of foundation depth of 581 the structure. 582

Figure 15 shows $d_{sc,end}/D$ as a function of h/D where h represents the over-topping height 583 for the case of Nakamura et al. (2008), the bore depth for Lavictoire (2014) and Shafiei et al. 584 (2015), and inundation depth in the current tests. These are equivalent measurements that 585 describe the water depth at the structure in all four set-ups. The current tests include 586 $d_{sc,end}/D$ recorded from the side corners of Structure 1 and the front face corner of Structure 587 2 (where the side view is unavailable). The CL25 waves which are the shortest period tested, 588 plot just above the edge of the Nakamura et al. (2008) 'long wave' data, indicating a greater 589 scour depth for the increase in period. The longer period TL49 and CL147 data also show 590 greater $d_{sc,max}/D$ for lower inundation heights than the Nakamura et al. (2008) 'long wave' 591 data which suggests that scour is sensitive to the duration of inundation. In the current 592 tests $\theta > \theta_{cr}$; the longer these live-bed conditions prevail, the faster the instantaneous rate 593 of scour, and larger the overall volume of sediment transport will be. 594

The CL147 and the TL49 waves plot closer to those of the Lavictoire (2014) and Shafiei 595 et al. (2015) bores over sand and gravel beds of similar h/D. There are differences to be 596 noted between the three investigations, however, which fundamentally look at two different 597 types of inundation on different shape structures (circular for Lavictoire 2014). The primary 598 difference is in the wave type; the current tests being unbroken cyclic inundation from a 599 long wave, as opposed to turbulent bore front inundation followed by a gradual reduction in 600 inundation height and velocity for Lavictoire (2014) and Shafiei et al. (2015). The velocities 601 of the bores are significantly higher than the inundation velocities in the current tests. The 602 overall length of inundation is comparable to the current tests, but the duration of the bore 603 fronts themselves is short, and comparable to the Nakamura et al. (2008) 'long waves' (where 604 maximum T = 14 s). The similarity in $d_{sc,max}/D$ as a function of h/D between the current 605 data, Lavictoire (2014) and Shafiei et al. (2015), all three of which have significantly greater 606 inundation time of the Nakamura et al. (2008) 'long wave' study, further suggests the length 607

of the inundation has bearing on the amount of scour.

It is also apparent from the data that the inundation time has more influence than the 609 inundation height. The effective inundation period of the TL49 waves, (i.e., the period of 610 the crest $T_{crest} \approx 25$ s) is the same as the CL25. However, h in TL49 is approximately 611 half the value, and yet $d_{sc,end}/D$ is only slightly lower. This is also despite \overline{U} being double 612 for the CL25 waves. Further, $d_{sc,end}/D$ for the TL49 waves is significantly greater than 613 the equivalent the Nakamura et al. (2008) 'long wave' crest-led data at equivalent h/D. 614 Nakamura et al. (2008) also concluded that inundation duration had a greater influence 615 than inundation height by comparing their solitary wave data to their 'long wave' data, 616 the latter showing greater $d_{sc,end}/D$. The long inundation time of the CL147 waves enables 617 the scouring flow field to become more fully established and suspend and transport more 618 sediment from the structures locality than the shorter waves. 619



Figure 15: $d_{sc,end}/D$ as a function of equivalent h/D for the current data and selected published experiments (see legend). The data from Shafiei et al. (2015) includes only that which is comparable to the current study. This is where the depth of the foundation $d_{foundation} > d_{sc,max}$ in that study.

620 4. Conclusions

The scour development and depth due to the inundation of tsunami length long waves at an onshore square structure is investigated. Three waves periods are tested; crest-led 147 s and 25 s, and a trough-led 49 s wave. These waves propagate over a 1:20 slope before
impinging on a flat sediment pit in which a square structure is placed.

The results indicate that the rate of onshore scour development varies with time due to the changes in flow velocity and depth. Larger scour depths were observed to be more dependent upon inundation time than velocity. Maximum scour depths occur at approximately $\frac{2}{3}T$, with the exception of the CL25. Slumping is observed towards the end of inundation, in some cases reducing the final scour depth by $\frac{1}{3}$ of its maximum. Therefore, scour depths inferred from post tsunami field surveys may underestimate the maximum scour depth.

Scour depths at the leading corner of the structure are up to 33% greater than at the cen-631 treline, indicating that equilibrium is not achieved during a single tsunami wave inundation. 632 Additionally, the data is compared against empirical predictions which tend to over-predict 633 the scour, further suggesting equilibrium is not achieved. While tsunami may involve subse-634 quent inundations and return flows, the usefulness of the theoretical equilibrium scour depth 635 as a measure of tsunami scour is as yet uncertain. More important variables are likely to 636 be the spatial and temporal location of $d_{sc,max}$, the differential of d_{sc} around the structure 637 (which may dynamically affect its response to loading) and $d_{sc,end}$. 638

To expand the data presented which is limited to three wave periods, it is compared with suitable published data. This enables the investigation of the effect of h, KC and inundation duration on the scour. It is shown that the inundation duration appears to most influence the scour depth. The influence of h is less apparent, while KC influence is not necessarily the same as observed for wind wave and current scour. This is stipulated to be due to transition of tsunami from wave-like to current-like flows during inundation.

Design guidelines for tsunami scour at onshore structures need to account for the transient 645 nature of $d_{sc,max}$ over the full period of inundation in order to accurately identify the greatest 646 scour depth a structure may experience during inundation, which must influence the forces 647 felt by the structure and its overall stability. This will include quantification of the spatial 648 and temporal location of $d_{sc,max}$ and the instantaneous variation of d_{sc} around the structure. 649 Additional investigations should look to refine this, investigating further the influence of 650 h, KC and duration to give a more robust empirical prediction method for tsunami scour. 651 Additionally, the return flow should be investigated. If the mechanism is similar to tidal 652 scour (e.g., McGovern et al. 2014) but on a shorter time-scale then the return flow is likely 653 to cause scour on the opposite side of the structure. McGovern et al. (2014) observed infilling 654 on the shoreward side initially, before an increasing scour depth at all sides. For solitary 655

wave inundation of a circular cylinder, Tonkin et al. (2003) showed the most significant scour
occurred due to a large vertical gradient in pore water pressure at the rear of the cylinder
during the return flow. This, along with the influence of variations in sediment and structure,
should be investigated.

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786 Appendix A.

Figures A.1 and A.2 show the front face of Structure 2 during test CL25b and TL49b respectively. Note the significantly more turbulent and suspended sediment opposed to the CL147 waves given in Figure 8.



Figure A.1: Image still from the front facing GoPro during the early stages of the CL25b inundation on Structure 2 showing a significant amount of suspended sediment.



Figure A.2: Image still from the front facing GoPro during the early stages of the TL49b inundation on Structure 2 showing a significant amount of suspended sediment.