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Scour and Scour-Induced Settlement of Cuboid Structures

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ABSTRACT

When a shallowly embedded structure is placed on the seabed without scour protection, scour can result in undermining and settlement of the structure. This process of undermining and settlement is studied experimentally in this paper for cuboid structures of various aspect ratio and density in steady current (with flow intensity close to unity). For the experiments reported, it was found that scour development undermined the front of the cuboid, resulting in forward rotation and a combination of progressive sinking and/or sliding of the cuboid into the scour hole. The undermining process was revealed using see-through glass cuboids, whilst the rate and extent of settlement was measured using image analysis to track the cuboid as it settles. Across the range of experiments reported it is found that once settlement starts, the rate of settlement and the final equilibrium settlement depth depend principally on the aspect ratio of the block, as opposed to the density of the cuboid. The rate and extent of settlement are compared to the rate and extent of scour for deeply embedded cuboid structures.

INTRODUCTION

When a structure is located on a mobile seabed and subjected to a steady current, it is well-known that the diversion of flow around it will result in amplified bed shear stresses and an increased capacity to mobilise sediment local to the structure (e.g. Whitehouse, 1998). If the structure is deeply embedded (such as a bridge pier) this local amplification can lead to the formation of a scour hole that will grow until it reaches some equilibrium profile. Alternatively, if the structure is shallowly embedded (such as pipelines, subsea structures and sea mines) local amplification can result in scour and undermining of the structure, leading to a reduction in bearing area and (i) subsequent settlement of the structure, or potentially (ii) toppling or rolling of the structure into the scour hole (see, e.g. Sumer and Fredsøe, 1994; Inman and Jenkins, 2002; Cataño-Lopera et al. 2011, respectively).

Arguably, the processes of scour-induced settlement and toppling/rolling involve more complex mechanics than that observed for deeply embedded structures, both because the movement of the structure is coupled to the scour process and because settlement of the structure involves a local failure of the underlying soil. Nevertheless, despite this additional complexity, the prevalence of deeply embedded structures in practice (particularly for bridge design) has meant that research on shallowly embedded structures has been much less common.

Friedrichs et al. (2016) recently synthesised a comprehensive set of available experimental observations concerning the self-burial of horizontal cylinders, spheres and tapered cylinders in steady current conditions. Using regression analysis, they conclude that for all three types of structure the Shields parameter is the main factor which influences the burial depth, relative to the diameter of the object; when the Shields parameter is increased (e.g. by increasing the current speed) the relative burial depth increases, presumably due to an increase in the potential for scour. However, despite the dominance of the Shields parameter, the analysis undertaken by Friedrichs et al. (2016) also indicated that the shape of the object and the density of the object appear to have an influence on burial depth - which hints at the complexity of the problem. Across all of the synthesised data, the burial depth also rarely exceeded the diameter, implying that scour and subsequent settlement rarely resulted in complete self-burial of the object.

More descriptive accounts of scour-induced settlement (or burial) of shallowly embedded structures have also been documented. For the case of short truncated cylinders and spheres, for example, Cataño-Lopera et al. (2005) and Truelsen et al. (2005) have shown that scour occurs preferentially in front of the structure and undermines the leading edge. As a result cylinders and spheres tend to roll forward and fall into the scour hole, resulting in both settlement and horizontal translation. Alternatively for short, tapered (i.e. cigar-shaped) cylinders, Rennie et al. (2017) have shown that the taper of the cylinder tends to cause the cylinder to rotate in the horizontal plane so as to become oblique to the incident flow direction during the initial stages of the scour process. As a result, the subsequent scour is amplified and the overall settlement is increased relative to a uniform cylinder of equivalent length.

These observations for short cylinders can be compared to experimental results concerning pipelines (i.e. long cylinders). Research work has shown that scour tends to propagate along a cylinder when it is long, resulting eventually in span shoulders that intermittently support the pipeline. If these span shoulders become sufficiently short bearing failure can occur, resulting in vertical settlement of the pipeline (Sumer and Fredsøe, 1994; Draper et al. 2015). Alternatively, if free-spanning sections of pipeline become too long, the pipeline may 'sag' down into the scour hole (Fredsøe et al. 1988).

Rectangular cuboids are a simple analogue for offshore infrastructure including artificial reefs, subsea foundations, manifolds, pipeline support structure and buckle initiators. As for cylinders and spheres, scour-induced settlement is expected for cuboid structures; however, it is

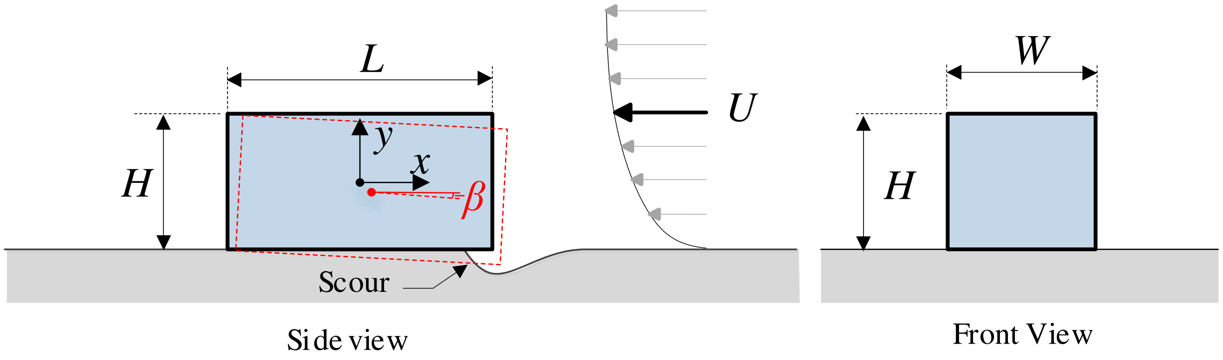


Figure 1: Experimental Setup.

easy to anticipate that the mechanism of settlement may be different. For instance, it is intuitive that in steady currents there should be a particular aspect ratio of cuboid, for a given set of conditions, in which the cuboid may or may not topple into a scour hole formed upstream of its base. Equally, in the event that toppling does not occur, one would expect that settlement may lead to rotation of the structure; thus the final orientation of the cuboid is not trivial.

Despite the application of cuboid structures to offshore infrastructure, only limited insight can be drawn from previous literature. For instance, Cataño-Lopera et al. (2011) and Inman and Jenkins (2002) have investigated settlement of flat-bottomed sea mines. However, each of these works were focused on wave conditions and conical structures with squat aspect ratios. Zhao et al. (2012) has conducted experiments on scour around subsea caissons in steady currents. However, in that case the caissons were deeply embedded and so the settlement process (and its effect on scour) was not captured.

The aim of this paper is to explore scour induced settlement of rectangular cuboids experimentally. A focus is placed on measuring the extent and rate of settlement across a range of cuboid densities and aspect ratios. Comparisons are made to scour around identical structures that are deeply embedded, as reported by Zhao et al. (2012).

EXPERIMENTAL PROGRAM

Experiments were performed in a conventional current flume located at The University of Western Australia. This flume measured 405 mm wide, 580 mm high and had a working length of ~13 m. A 300 mm deep recess extending over the middle 1140 mm of the flume floor was filled with a uniform silica sediment having a median grain diameter of d_{50} =0.6 mm, no fines content and a coefficient of uniformity of ~1.7. In each experiment, a rectangular cuboid was placed in the center of the flume directly onto the sediment bed (see Figure 1). Each cuboid had a length L, measured parallel to the flow direction, and a height equal to its width of H (set to 50 mm for all models). A range of materials were used for the cuboids, including glass (density of 2400 kg/m^3), steel (7700 kg/m^3) and lead (11340 kg/m^3), so as to investigate the effect of density on the settlement process. The aspect ratio L/H of the cuboids varied between 1 to 3. These aspect ratios were sufficiently squat such that the cuboids did not topple forwards (Johannsen, 2020), and covered a practical range for subsea structures used across a range of applications in coastal and offshore engineering.

In each experiment, a velocity of U =0.351 m/s was run (referenced to a height of 50 mm above the sand bed, e.g. the top of the cuboids). This corresponded to a flow intensity of 1.15 (i.e. flow intensity was 1.15 times the threshold velocity, U_{cr}) and allowed for relatively deep scour without significant influence from bed forms. It also ensured that the hydrodynamic force on the cuboids (estimated assuming a drag coefficient of order unit) was negligible compared to the weight of the blocks, which is the expected situation in any practical application. The water depth was held at ~250 mm to avoid blockage effects. A dimensional analysis and some commentary on the scaling assumptions are given in Johannsen (2020).

Table 1 presents an overview of the experiments undertaken. In each experiment, the sediment was prepared in a loose state to counteract the fact that the stresses in the soil due to the cuboids are small at model scale. The internal friction angle (inferred from the angle of repose observed by creating a mound of sediment) was measured to be 30.5 deg.

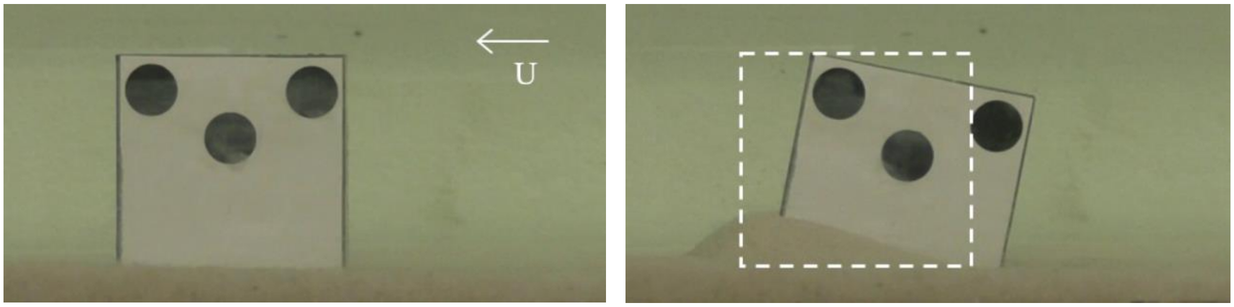
In each experiment, a video camera was placed above and to the side of the flume. Three circles were placed on the side of the cuboids (see Figure 2 to see the circles); these were then tracked via thresh-holding to locate the position of the center of the block and its rotation in each video frame. The rate and extent of settlement could then be computed.

Table 1: List of experiments undertaken

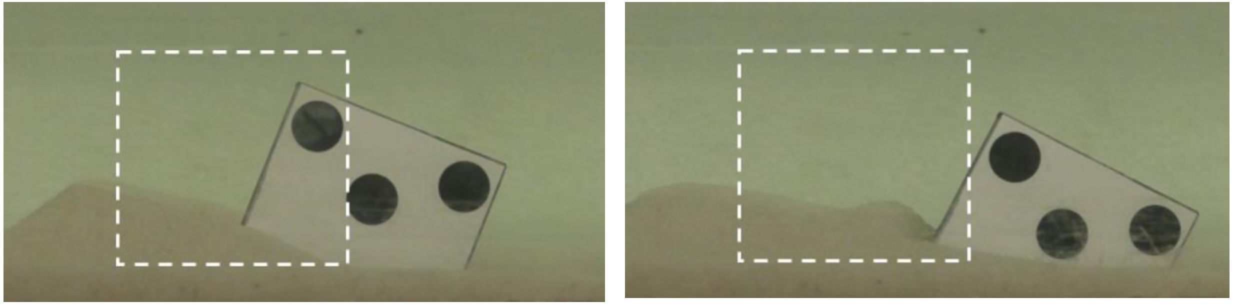
Experiment	**Experimental Parameters**		
	L/H	**Cuboid Density (Material)**	U/U_{cr}
G1	1	2400 kg/m^3 (Glass)	1.15
G2	1.6		
G3	2		
S1	1	7700 kg/m^3 (Steel)	
S2	1.6		
S3	2		
S4	3		
L1	1	11340 kg/m^3 (Lead)	
L2	1.6		
L3	2		

EXAMPLE OF SETTLEMENT

Figure 2 and Figure 3 presents several snapshots of the scour hole development and the settlement (rotation and translation) for experiment L1. The settlement process is characterized by the formation of a scour hole upstream of the cuboid, which leads via undermining to instability and a combination of translation and rotation of the cuboid. Figure 4 presents the settlement, measured in terms of the translation of the center of the block (x, y) and the rotation of the block β, as defined in Figure 1. It can be seen that there is an initial delay until settlement starts – during this period of time scour is undermining the block. Once settlement starts the time development is

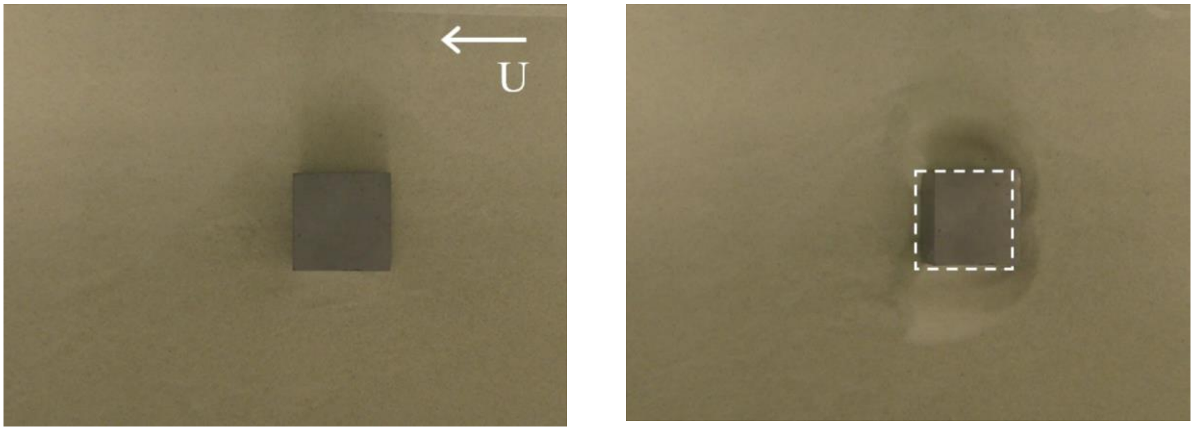


(a) 0 mins (b) 2 mins

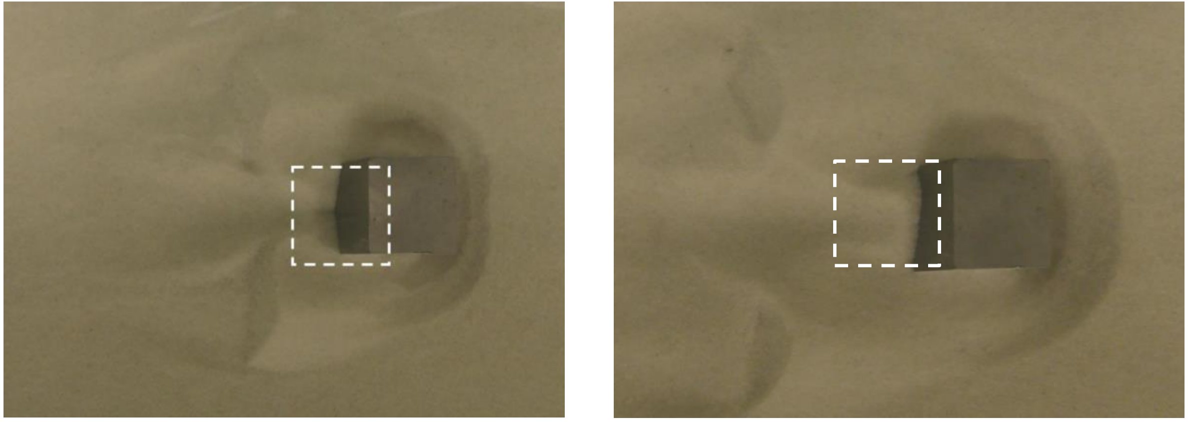


(c) 10 mins (d) 40 mins

Figure 2: Snapshots (from the side) for experiment L1.

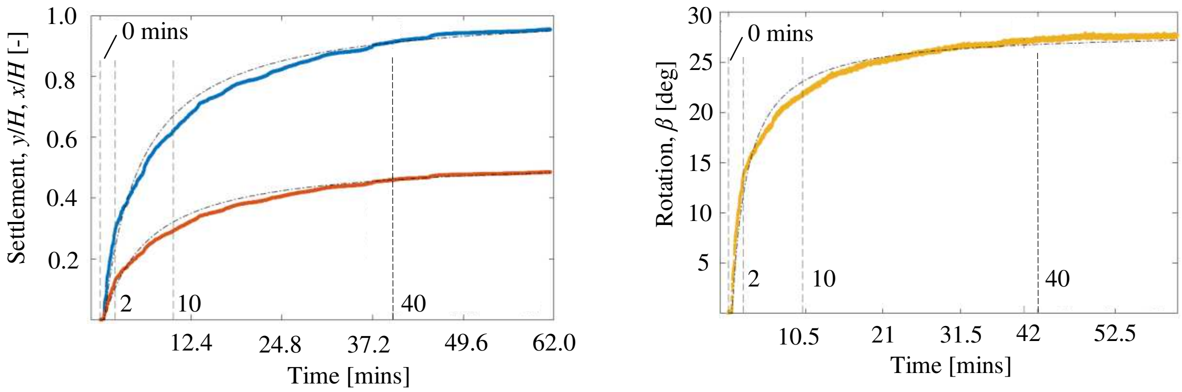


(a) 0 mins (b) 2 mins



(c) 10 mins (d) 40 mins

Figure 3: Snapshots (from above) for experiment L1.



(a) (b)

Figure 4: Time development of settlement for L1. (a) Translations (top line is horizontal and bottom line is vertical), (b) Rotation. See Figure 1 for definitions.

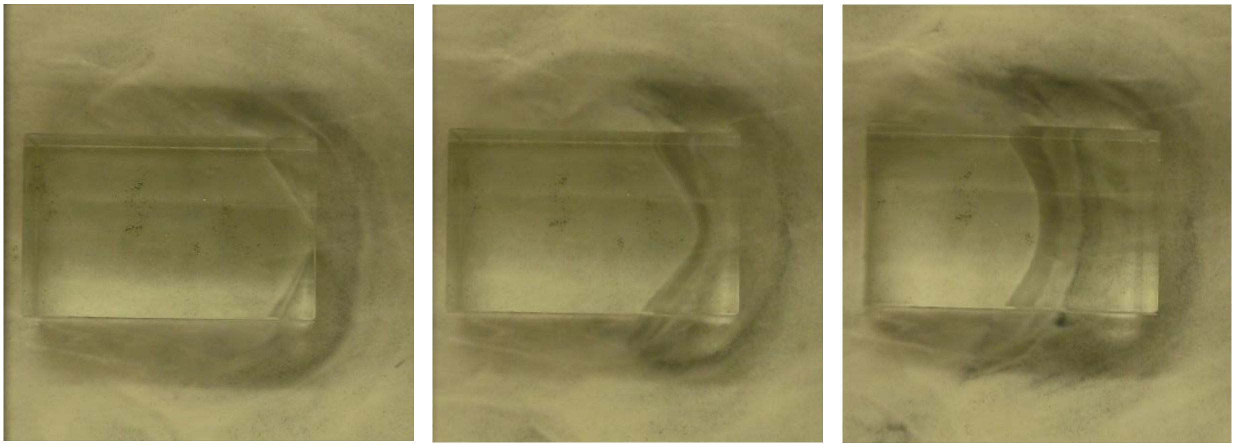


Figure 5: Snapshots from top video showing undermining in G2. In all cases $t < t_i$ and flow from the right.

similar to that observed for scour development around rigid objects: settlement is fast initially and then slows as it limits towards an equilibrium. In this example experiment and across all other experiments, the rotation of the block approaches an equilibrium value faster than the translation.

The undermining process cannot be seen directly in Figure 3 because a lead block is shown. Figure 5 gives some example results from G2 prior to the start of settlement.

The settlement process observed for experiment L1 was similar to that observed across all experiments. In summary, the process consisted of three stages:

1. The block is stable initially, whilst scour develops and undermines the block. Eventually, the undermining becomes sufficient to result in local bearing failure and movement of the block into the scour hole.
2. The block translates and rotates into the scour hole.
3. The block no longer rotates appreciably and just translates as the block effectively ‘slides’ upstream into the scour hole at an approximately constant angle.

Depending on the density of the cuboid the sliding observed in stage 3 either occurred such that the equilibrium rotation angle of the block coincided with the angle at which it slid (glass and steel), or was less than the angle at which it slid (lead). The latter means that the block moves vertically down at a steeper angle than the angle the block is positioned relative to the horizontal.

In Figure 4 fits to each of the curves are also shown. These have the following functional form (shown below for vertical settlement only):

$$y(t) = y_e \frac{t - t_i}{t - t_i + T_y} \tag{1}$$

where y_e represents the equilibrium vertical settlement, T_y the time scale of vertical settlement and t_i is the time prior to settlement starting. Fitted equilibrium settlements and time scales are discussed in the next section for the entire range of experiments.

SETTLEMENT EXTENT AND RATE

Figure 6 presents the equilibrium vertical settlement depth for each of the experiments as a function of the aspect ratio of the different cuboids (note several repeat tests are also included to indicate variability across tests). It should be noted that all of the equilibrium settlements in Figure 6 were much larger that the negligible amount of settlement observed when the block was first placed on the flat sand bed prior to the start of the experiment. It can be seen that the settlement depth in Figure 6 reduces as aspect ratio increases, but there is no clear trend with density. The dependency on aspect ratio may be explained by the fact that less undermining is required to cause rotation for shorter blocks and a relatively larger scour hole is formed around the shorter cuboids as they settle; this second observation is somewhat consistent with the slightly deeper scour holes formed around deeply embedded short caissons reported by Zhao et al. (2012). The limited dependency on density (or at best a secondary influence due to density) is consistent with that observed in the literature for a variety of structures. This is often explained by the fact that the settlement is a result of scour, which will depend primarily on the structure geometry and flow velocity, provided the density does not significantly alter the mode of settlement and, in turn, the hydrodynamic properties of the structure as it settles.

Figure 6 also presents a comparison of the measured settlement depths to the scour depth measured in two fixed-structure scour experiments by Zhao et al. (2012) for cuboids with aspect ratio of $L/H = 1$ and 2. In these two scour experiments, the initial shape of the structure above the seabed was identical to the cuboids tested in the present work; however, the structures were deeply embedded such that undermining and settlement could not occur. It can be seen that the settlement depth is always lower than the scour depth. This result implies that settlement does not augment scour in the present experiments.

Equilibrium rotation angles (not plotted) displayed a similar dependency on aspect ratio to the vertical settlement depth. The equilibrium rotation angle also showed limited trends with density; however, the trajectory of the blocks were dependent on density. Work is ongoing to understand this latter trend by better investigating the geotechnical aspects of the settlement process.

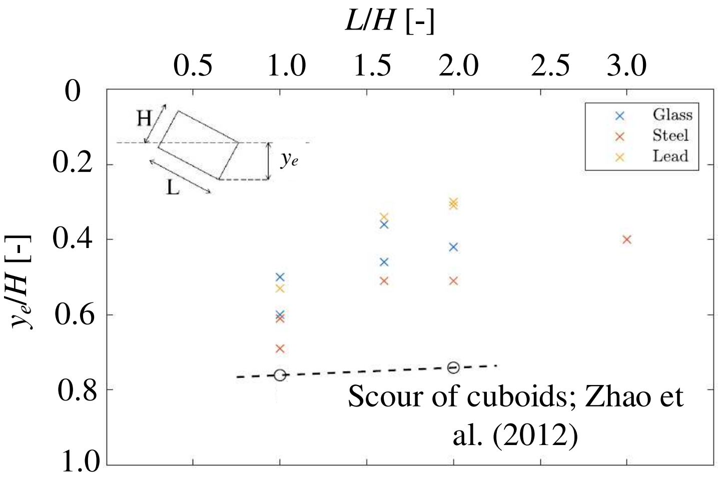


Figure 6: Equilibrium vertical settlement depth. Scour depth results due to Zhao et al. (2012) are also shown for deeply embedded cuboid structures.

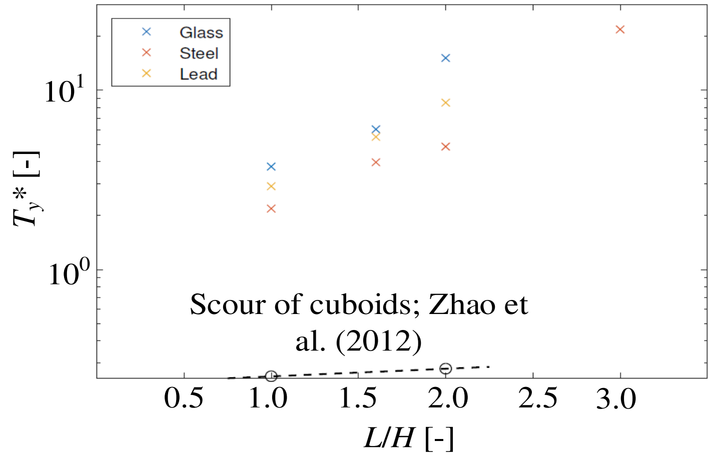


Figure 7: Time scale of the vertical settlement process. Time scale of scour results due to Zhao et al. (2012) are also shown for deeply embedded cuboid structures.

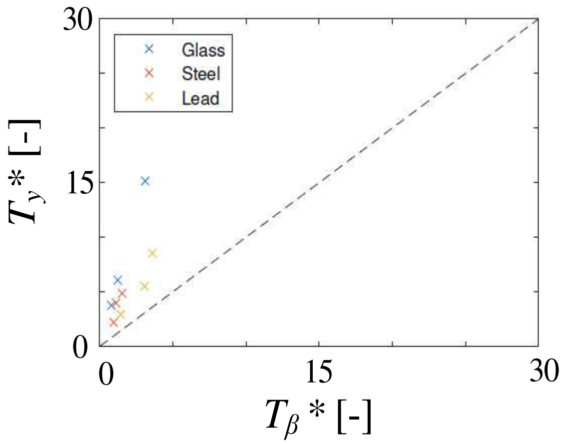


Figure 8: Timescales for translation and rotation of the cuboids during settlement.

Figure 7 compares time scales of vertical settlement for each of the cuboids tested as a function of aspect ratio. It can be seen that the time scale increases with aspect ratio; thus, longer cuboids take longer to settle despite settling to smaller relative depths. The time scale for the glass blocks is always less than for lead, although the steel blocks take longer than the lead. Hence, for the limited number of experiments reported herein there is no clear trend with density.

Figure 7 also presents the time scale of scour for the same cuboid structures plotted in Figure 6 from Zhao et al. (2012). As might be expected, settlement is a slower process than scour of a fixed structure by about one order of magnitude in terms of time scale. To enable the comparison in Figure 7, the time scales have been made non-dimensional according to:

$$T_y^* = T_y \frac{(g(s-1)d_{50}^3)^{1/2}}{H^2} \tag{2}$$

where g is acceleration due to gravity, s is relative density of the sediment (taken to be 2.65) and d_{50} is the median grain diameter. A similar equation has been used for the other time scales (e.g. T_β). The denominator in Equation (2) has been chosen to be H because the scour volume, per unit width, is expected to scale principally on the square of the cuboid width, which for the geometry used herein is equal to the height H. The estimated error in time scale values are ± 20 %.

Finally, Figure 8 shows the time scale for vertical settlement plotted against the time scale for cuboid rotation for each experiment. As discussed earlier in this paper, rotation happens much faster than translation in each experiment. This helps to demonstrate that the settlement is characterized initially by combined rotation and translation, followed by a stage in which the cuboid simply translates without rotation into the scour hole.

CONCLUSIONS

A range of experiments have been undertaken using rectangular cuboids to investigate scour-induced settlement. It has been found, for the range of cuboid geometry and density considered, the settlement process has three stages characterized by (1) scour-induced undermining, (2) settlement via translation and rotation, and (3) settlement via translation only.

Image analysis was used successfully to track the cuboid settlement. Each experiment revealed that the settlement process is qualitatively similar to that often observed for scour processes; the settlement is fast initially and then slows towards an equilibrium value. The equilibrium vertical settlement was seen to be generally smaller than the equilibrium scour depth for an equivalent, deeply embedded structure. It was also shown to depend primarily on cuboid aspect ratio rather than cuboid density (at least in the present experiments).

The time scale of the vertical settlement process was also determined and shown to increase with cuboid aspect ratio. In all cases, this settlement process was about one-order of magnitude slower than that observed for scour of an equivalent deeply embedded structure.

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