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Field and laboratory investigation into scour around breakwaters

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Abstract

Coastal scour accounts for a significant proportion of the damage to marine structures. It is therefore important to be able to measure, model and predict scour effects to inform the design of new structures and to assess potential damage to existing ones. The aim of this project was to compare the results from field surveys to those obtained in a marine test laboratory. Since this project employed small scale modelling this provided a further opportunity to compare results with those obtained in previous published studies. This project has compared collected data from two coastal structures with results obtained from modelling in the COAST facility at the University of Plymouth. The results obtained have validated the use of this technique. Scouring was investigated in the vicinity of two breakwater structures; the Falmouth Eastern breakwater and the Mount Batten breakwater. A bathymetric survey was conducted in the vicinity of Mount Batten breakwater and previously published data from the Falmouth breakwater was obtained. This data was used to model the sea bed profile at the end of each of the structures. Small scale models of these two breakwaters were designed and built for this project and tested in laboratory facilities. Data collected from the field surveys was subsequently compared to results collected from laboratory testing and then the differences were analysed. It was found that expected scour pits were not present at the end of either structure. This indicates how complex scour in coastal areas is to predict and model, it is likely that variables such as such tides, bidirectional currents, interaction with other structures and turbulence from marine vessels accounts for the absence of the usual scour patterns in these cases. However the data collected was valuable in developing the test methodology and will be helpful in future work. The similarity between the small scale laboratory results obtained and previously published literature for larger scale modelling indicates that this method of testing could be considered valid for the future design and development of costal structures as well as providing a tool to model the behaviour of such structures in hostile conditions. There are economic advantages to being able to test in smaller less expensive facilities and this project has demonstrated the validity of such small scale testing.

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Nomenclature

D = Diameter of structure (m)

D_x = Diameter of bed material of which x% are smaller, (m)

d_0 = Nozzle diameter (m)

Fr = Froude Number directly upstream of the pier $= \frac{U}{\sqrt{gh}}$

g = Acceleration due to gravity, (9.81 m/s^2)

M = Shear stress amplification factor

p = Coefficient relating to shape of S(t) curve

Q = Flow rate in the flume (m^3/s)

Re = Reynolds Number $= \frac{UD}{v}$

S_e = Equilibrium scour depth (m)

S(t) = Depth of scour pit relative to time (s)

T = Time scale for scour (s)

T_{cr} = Critical value for sediment motion

T_{jet} = Maximum value of bed shear stress (Pa)

T_0 = Bed shear stress (Pa)

V = Mean velocity of flow directly at the end of the model, (m/s)

Z_n = Height of nozzle above bed (m)

ρ = Density of water (Kg/m$^{3)}$

Introduction

The purpose of this project is to validate laboratory techniques used to model the impacts of scour. In order to conduct this project a significant amount of data was collected from field surveys and from extensive testing conducted within the COAST Laboratories in Plymouth. The conclusions of this project show a strong correlation between the results obtained through testing in laboratories and previous similar larger scale published studies.

Background information

Coastal structures are an important part of any coastline; they provide shelter and protection from tides and waves. They additionally assist in the control of coastal shaping and sediment transport. There are many different types of coastal structures including breakwaters, groynes, jetties, seawalls and harbours (Dean & Dalrymple, 2002).

Scour is the removal of bed material in the close vicinity of a structure by hydrodynamic forces (Marcinkowski, 2004). The impact of scour is by its definition localised however the effect of scour around the foundation of a structure can have significant impacts on the economic and service life of many coastal structures (Hales, 1980).

An industry report conducted by ICE (1985) recognised the importance of addressing the impact scour has on coastal structures and called for more research into the behaviour and preventative design solutions for scour in support of the civil engineering community (Whitehouse, 1998).

A report published by CIRIA in 1986 titled “Sea Wall Performance in the UK” concluded that scour around the base of a structure, also known as the toe, was the leading factor in damage sustained by seawall structures. Historical studies reveal that this localised scour, at the toe of sea walls, was accountable for around 12% of collapses, breaches or loss of fill material for the cases reviewed. A design manual for “Sea wall design” was published by CIRIA in 1992 as a response to the scouring issue (CIRIA, 1992).

It is important to recognise the difference between erosion and scour. Whilst erosion refers to a general lowering of the ground surface over a wide area, scour refers to a localized loss of sediment, often around a foundation element (U.S Department of Homeland Security, 2009). It is this localised loss of sediment that leads to the undermining and eventual collapse of structures.

Erosion presents itself as the wearing away of the ground surface as a result of the movement of wind, water or ice and is a gradual process often taking many years to become a significant problem. Scour in comparison is a faster process, usually caused by fast turbulent flows. Typically large scour events occur during severe weather conditions such as storms where turbulence and the velocity of a body of water are often amplified (U.S Department of Homeland Security, 2009). It is this acceleration in water movement that tends to dislodge the sediment at the bottom of a structure.

Scour around coastal structures can cause catastrophic failure as demonstrated during the storms of 2013-14 when the foundations of the sea wall at Dawlish on the South Devon coast of England were compromised; the sea wall collapsed destroying the rail link to parts of Devon and Cornwall (Ewens, 2015).

Purpose and objectives of the project

The overall objective of this project is to investigate the scour at the end of two coastal structures at a small scale and validate the industrial value of small scale testing. Both of these structures are located off the South West Coast of England, one in Plymouth Sound – the Mount Batten breakwater and on in Falmouth Harbour – the Eastern jetty breakwater.

This project concentrates on the accuracy of physical modelling on a small scale compared to data collected in the field. Field work involved a bathymetric survey around the Mount Batten breakwater undertaken from a boat using specialist equipment over a period of five hours, and the gathering of existing bathymetric survey of the Falmouth breakwater through research. Scour data gathered from around the end of the case study structures was reviewed and used to design and produce scaled models for use in the COAST Laboratory in Plymouth. The behaviour of the models was tested and monitored and the shape and depth of the scour holes created was measured in the laboratory and compared to the field data results. Thus validity of the experiments and the accuracy of this method of testing were quantified.

There are three main methods used in industry to observe the behaviour of a marine structure under conditions experienced during its life; field measurements, physical modelling and numerical modelling (Hughes, 1993). In many cases physical modelling is the more favoured approach due to cost advantages over field measurements and concerns over the accuracy of some numerical techniques. This project investigates the physical modelling of scouring on a small scale, concentrating on its accuracy using two case studies.

Scope and limitations of the project

The research undertaken to support this project consists of both field work as well as laboratory testing in which a bathymetric survey and flume scour experiments were undertaken. The bathymetric survey was affected by the weather and tides around the Mount Batten breakwater and therefore was not undertaken until late January 2016 when suitable and safe weather conditions were present. In the laboratory the tests were limited to a time period of 40 minutes each. This was observed, during preliminary testing, to be the time taken for scour to reach equilibrium for the largest water depth tested. All experiments were conducted under clearwater scour conditions, where there is no bed movement upstream of the structure (Whitehouse, 2006). This ensured that a representation of localised scour was obtained without interference from bed transportation. Due to the nature of the apparatus unidirectional flow at a constant flow rate was achievable. This offers a representation of the behaviour of a fixed structure under a fixed directional flow with no currents, traffic or tidal interference. This limitation in variable parameters allows this testing to be more readily available as the cost and complexity of testing is kept low. It was the intention to quantify the credibility of this method of modelling as an alternative to other methods currently used in the civil and coastal engineering industry.

Method of approach

This project involved researching scour around coastal structures using three main methods; desk study, field work and laboratory tests. The first consisted of undertaking a literature review of current and available information about scour and the parameters that affect the process; this then led into a more specific review of coastal scour and the behaviour of structures in the marine environment. A review of the prediction methods currently used and preventative designs for scour was discussed along with the process and limitations of physical, numerical and field data modelling. Secondly a bathymetric data survey of the Mount Batten breakwater was undertaken to gather information that was used in the laboratory in scaled models. Two different groups of tests were undertaken in the COAST Laboratory located at Plymouth University, the first investigated the limitations of the laboratory apparatus and defined experimental parameters for the second group of tests. The second group consisted of subjecting two purpose built scaled models to a predetermined set of conditions whilst monitoring the scour formations at the end of each structure. The aim of this project was to obtain a deeper understanding of the process of scour in the marine environment through the application of research, enabling the accuracy of results collected to be assessed in a controlled environment.

Synopsis of report

Chapter 2 of this report gives an overview of the literature studied around the subject of scour and concentrates on coastal scour and the impact and effect that various parameters have on structures in the marine environment. Principal scour prediction methods and preventative solutions are also identified in this chapter.

The next chapter provides a detailed review of the Falmouth Eastern breakwater and Mount Batten breakwater structures.

Chapter 4 provides a detailed description of the apparatus, procedures and methods used in the investigation of project specific parameters as well as giving an overview of field data collection and the processes involved in applying this information in the laboratory.

The following chapter contains a review of the testing and analysis of the scaled models and provides information about the procedures followed in the final tests. Results from the experiments including data and graphical representations of data are presented in Chapter 6.

Chapter 7 contains discussion and analysis of the results along with suggestions for the future use and application of small scale modelling in the coastal and civil engineering industry. The conclusion of this project is located in the last chapter.

Literature review

Introduction

As part of this research project a review of the current literature on scouring was conducted. The review starts with considering the broad definitions and categories of scour documented including those that have different impacts in rivers and on coastal areas. The review then leads into a closer in-depth evaluation of published material regarding the importance of the various impacts of this particular form of erosion on the design of coastal structures, this includes the parameters affecting scour. The current prediction and protection methods are also reviewed.

Definition of scour

In the case of coastal structures, scour is the removal of bed material in proximity to the structure (Hughes, 2002). In rivers or streams normal flowing water can cause scour in the form of the erosion or removal of bed or bank material from a structure’s foundations (Kattell & Eriksson, 1998).

The scour event experienced by a structure can be so large and powerful that it undermines the entire integrity of the structure concerned and may compromise the foundations leading to failure.

River scour has been widely researched and there is a large body of literature investigating the different parameters that affect the scouring process in this environment. There is considerably less research on coastal scour and the variable parameters which affect it. It is suggested that the lack of research is due to the complexity of the flow and scour processes in conjunction with waves and currents in the marine environment, the increase in variable parameters amplifies the difficulty in studying marine scour. Following investigation into the failure of breakwaters it was highlighted that a deeper understanding of knowledge about marine scour is required in the design phase for many structures (Oumeraci, 1994).

When a structure is placed in a marine environment the flow pattern around it will be affected causing eddies and vortices, these changes in the flow pattern will cause the removal of local sediment around the base of the structures (Whitehouse, 1998). The nature of the structure and the prevailing direction of water flow will determine the highly complex flow patterns around the structure. In the 1980’s and early 1990’s an increase in knowledge and investigations of scour around offshore coastal structures, simple monopoles and pipelines highlighted a relationship between separation vortices and scour (Herbich, et al., 1984). Studies on the effects of right angle wave attack on a vertical breakwater have been undertaken and findings suggest within these parameters scour forms in front of the breakwater (De Best, 1971; Fowler, 1992; Irie & Nadaoka, 1984; Shi-Leng, 1981). In contrast a study undertaken by Sumer and Fredsøe (1997) investigating the scour around the head of a breakwater suggested separation vortices around the leeward side of the structure contributed to the scouring process.

Types of scouring

There are many variables affecting scour and therefore a number of different scouring effects, only some of which can be accounted for in modelling due to the levels of complexity involved these include; tide, current, salinity, seabed profile, waves, storms, wind, manmade structures, the erosion of coastlines and shipping traffic are amongst the few that can be modelled (Whitehouse, 2006).

Coastal scour is a physical response to waves and currents which involves the removal of sediment locally around a structure; commonly classified as either local scour, global or dishpan scour or overall sea bed scour. Global scour can appear as a shallower larger area of erosion usually under or around a structure; this type of event usually applies to structures such as oil rigs and piers. In most cases both global and local types of scour appear under and around the piles of the structure. Overall sea bed scour is the movement of the sea bed and the erosion and deposition of bed material, which is caused when the bed material is scoured out from around a structure and deposited behind the structure having been transported by eddies and vortices, this was clearly shown in the laboratory testing undertaken for this project see Figure 1 below.

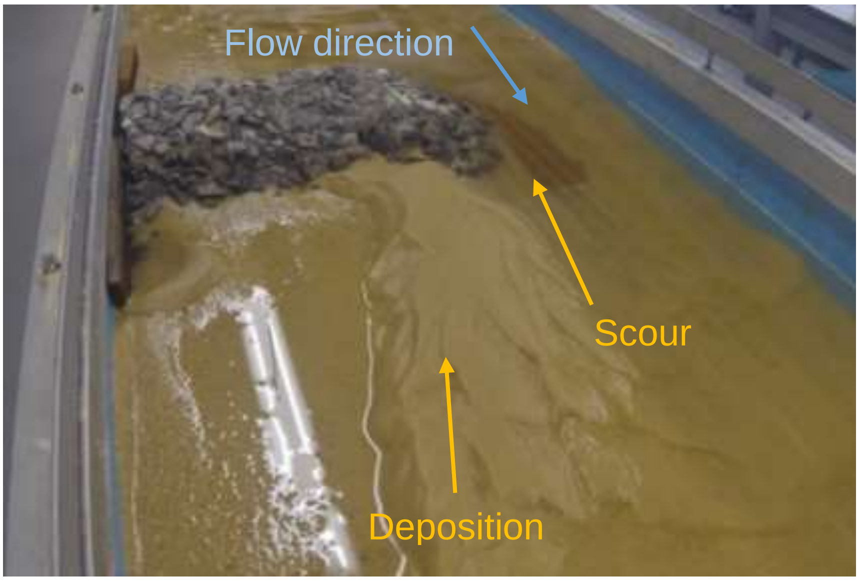

Figure 1: Scouring and deposition of bed material downstream of a structure.

This erosion of material is caused by the presence of the structure disturbing the flow of the water, this can narrow the channel of flow leading to an increase in the speed of the flow through the relationship of Q = VA where Q is the flow rate, V is the velocity and A is the cross sectional area. This increase of velocity leads to an increase in turbulence which generates vortices which in turn lead to the removal of bed material close to the structure (Whitehouse, 1998).

Whitehouse (1998) further discussed the process of clearwater scour which can occur when the upstream flow speed is insufficient to displace any bed material but the presence of the structure causes the flow speed adjacent to the structure to be increased causing local bed movement. This process usually occurs during neap tides and is known as clearwater scour as there is no bed movement upstream of the structure.

Clearwater scour is described in the river scouring application as the point where the bed shear stress, $\tau_{0,}$ is less than the critical value for sediment motion, τ_{cr}, but is greater that τ_{cr} /M, where M is the shear stress amplification factor adjacent to the structure. The alternative to clearwater scour is Live bed scour where $\tau_0 > \tau_{cr}$ indicating that there is bed movement everywhere and therefore bed material is being moved from upstream of a structure as well as locally around a structure (Whitehouse, 1998).

Coastal scour

Structures such as harbours, marinas and breakwaters provide protection from the effects of the sea and create the conditions for economic growth in a marine or coastal environment and are therefore essential for the survival of many communities. Structures such as groynes and offshore breakwaters aid in the manipulation and protection of coastlines and can reduce the impact of longshore drift and help control the distribution of local sediment. When these structures fail the impact can be catastrophic. A recent well known example of structural failure was the Dawlish sea wall which failed in 2014 during a prolonged period of bad weather.

In this example the heavy storms and large surge waves caused localised scouring at the toe of the structure which in turn undermined the wall causing it to collapse.

This sea wall was protecting the only rail line that linked the far south-west to East Devon and the rest of the country. As a result of this all access via train was suspended for around eight weeks for repairs which cost approximately to £35 million (Kay, 2014). This not only caused huge disruption to thousands of commuters and businesses that rely on this method of travel but also caused a significant increase in traffic and disruption of the road network in particular on the A38.

For reasons believed to be linked to a rise in sea levels and average global temperature there is evidence of a dramatic increase in the severity and frequency of storms in many areas of the world particularly in this case along the South West coast of the UK (Haigh, et al., 2010). Most structures are designed to withstand a 1 in 100 year storm event wave however, in 2013/14, the South West coast experienced five storms of this strength in two months (MetOffice, 2014).

As a result of such extreme weather events more accurate prediction of the behaviour of structures in different conditions will be necessary in order to provide researchers with an indication of a structure's capability and aid in the development of prevention methods. This will also show which structures might need to be improved in preparation for such future extreme weather events.

Parameters that affect scour

It has been noted that, under certain sets of parameters and conditions, scour around a structure happens surprisingly quickly and stabilises at a maximum depth. Some research has provided numerical techniques to predict and measure such events. Under any environmental combination of conditions, as long as they are constant, the depth and area of scour around a structure will eventually reach its equilibrium (Breusers, 1972; FredsØe & Sumer, 2002).

The following formula has been found to be an accurate analysis for the depth of a scour pit (S) with time (t) around a monopile in steady conditions (flow and current) with no waves.

$$S(t) = S_e \left[1 - \exp(-\frac{t}{T})^p\right]$$

(Harris, et al., 2010; Petersen, et al., 2015)

S_e is the equilibrium scour depth as t tends to infinity. T is the time scale for scour and p is a coefficient relating to the shape of the S(t) curve.

During the scouring process wake vortices are formed by the disruption in flow and eddies occur in a "shedding" fashion downstream in a periodic manner. The wake vortex picks up the sediments and deposits them downstream roughly up to a distance of 8D where D is the diameter of the structure; in this case a pile. The shedding frequency of the vortices occur at a Strouhal number of approximately 0.2 and within a Reynolds number range of 10^2 - 10^5. Note that in higher currents and flow speeds or with wider piles the regularity of eddies becomes less periodic and more disordered. This is relationship is represented by the following equation.

$$S(t) = \frac{f_v D}{U}$$

(Hjorth, 1975)

It is important to recognise the implications of bed liquefaction when evaluating the process of scour, Liquefaction can cause the top layers of the bed material to become more susceptible to erosion and scour. Liquefaction is likely to occur during steep storm waves and can be one of the causes of global scour around offshore structures.

Liquefaction occurs when the shear stress of a material is very low or close to zero causing the individual particles to be unconstrained by neighbouring particles. (Somerville & Paul, 1983)

Rocking of structures during high energy waves can also add to the scouring process, due to a build-up in the pore water pressure causing a piping effect which can cause foundations to fail. A case study undertaken on the tower in Christchurch Bay on the South coast of England showed the failure was due to this build up in pore water pressure caused by a rocking movement during storm waves (Bishop, 1980).

Miscellaneous scouring

Scouring, as a result of vertical or horizontal jets, is due the shear stress in the area being subjected to the jet decreasing and can be predicted using the following equation

$$\tau_{jet} = 0.16\rho \, \frac{U_o^2}{(\frac{Z_n}{d_o})^2}$$

Where τ_{jet} is the maximum value of the bed shear stress, Z_n is the height of the nozzle above the bed with diameter d_o, ρ is the density of the jetting water and U_o is the velocity of the jetting water. This type of scour event is common around pipe outlets (Beltaos & Rajaratnam, 2010).

Scour due to manoeuvring vessels is a particularly important consideration in the case of port and harbour design. Propeller wash can cause scour around a structure as the vessel passes, it is important to take this into consideration during design and construction of structures that will be subjected to this kind of wash. An expression for the scour depth incurred through this process is defined by Verhey (1983) and later used by Hamill (1988), where the dimensions of the propeller and the distance between bed and propeller combined with a function of Froude number F_o give a reliable prediction method for scour depth (Hamill, 1988). This prediction method allows for the design of bed protection that can withstand scouring forces. A formula for this prediction method is displayed below.

$$\frac{d_{s,t}}{D_p} = 0.105F_0^{0.852}(\frac{y_0}{D_p})^{-0.991}(\frac{d_{50}}{D_p})^{0.315}(\frac{U_0 t}{D_p})^{0.168}$$

(Hamill, 1988)

Where D_p is propeller diameter, y_0 is the distance from propeller to the sea bed.

Scour prediction

Laboratory experiments usually consist of scale versions of structures that are placed in a bed of material with the desired characteristics, usually sand, and subjected to varying conditions such as waves, currents, tides or a combination of these. In such controlled conditions structural changes and bed behaviours can be measured effectively, producing results for further detailed analysis.

It is important to note that while geometric similarity is easily achievable through dimensional scaling, dynamic similarity is generally harder to achieve due to the physical properties of the different variables involved. To model water on a small scale petrol may be used; however this raises some obvious serious safety concerns (Hamill, 2011). Where it is not feasible to scale properties of the model correctly and safely, results obtained through small scale modelling should be used as an indication of behaviour only.

Model tests are an effective method for studying scour patterns, particularly for structures of complex geometry, used in the design stage (ICE, 1985).

It is also considered economically advantageous to undertake scaled physical modelling of structures for hydraulic applications due to the versatility and ease of use compared with that of numerical modelling. Small scale physical modelling for scour situations is ideal as its allows 3-dimensional scour to be investigated easily and with a good level of precision, compared to the complexity and margin for human error involved in some computational numerical models, due to such a complex set of variables involved. Not only can principal theories about generic structures be tested in different conditions but also site-specific investigations of existing structures in hypothetical or predicted environmental conditions may be conducted.

In this project a review of the following literature led to the decision to use a 3-dimensional investigation through small scale modelling. Most scaled tests are undertaken in flumes of typical length 5m – 50m and width 0.3m – 3m, the average water depths used in these flumes is between 0.2m and 2m. The scale of models used in the studies varied from 1:40 and 1:50 used by Irie and Nadaoka (1984), 1:20 used by Shi-Leng (1981) and a 1:7.5 scale model used by Fowler (1992).

The design of these tests was influenced by results showing the minimum water depth that should be used is 0.02m, due to the dynamic scaling issues (see above) as the water surface friction coefficient becomes too high to obtain an accurate result at very shallow depths (Hamill, 2011).

This project investigated a unidirectional current produced by a pump system at one end of the flume. However in other facilities it is possible to achieve multi directional flows, waves, currents, tides, storm surges and tsunamis (HR Wallingford, 2014).

For situations where the maximum depth of the scour hole is required then clearwater scour conditions can be used, however live bed scour can be used for applications that require a variety of different scenarios to be evaluated.

The principle for scaling of waves and currents for laboratory testing is well documented and understood and employs Reynolds and Froude number scaling. However in practice it is often found that due to the many variable parameters involved in the test exact scaling is not necessarily achievable. These scaling effects become smaller and more easily controlled with a larger scale of model. The majority of hydraulic models are scaled using Froude scaling equations. This maintains the general rule that the Froude number of the prototype must be the same as that of the model to ensure continuity and accuracy (Hamill, 2011).

The following two formulae represent Froude and Reynolds number respectively. Both are used in model scaling however Reynolds number is generally used as a checking method to ensure the model is within the correct roughness range (Hughes, 1993).

$$Fr = \frac{U}{\sqrt{gh}}$$

Where U is flow speed, g is gravity and h is water depth.

$$Re = \frac{UD}{\upsilon}$$

Where D is a length scale, usually water depth or pile diameter and υ is viscosity of the liquid.

The following points should be considered when deriving scaling relationships; rotational slip failure of the bed material, the pressure gradient effects including density, consolidation and liquefaction and the scour friction factor for the bed shear stress. However these considerations may not all be easily accounted for in small scale modelling.

A relationship between the Keulegan-Carpenter number and scour depth has been identified by Sumer and Fredsøe (1997) through testing of model breakwaters by showing that with the increase of KC and increase in the scour depth can be observed. The equation is presented below.

$$\frac{S}{B} = 0.5C\;[1 - \exp\{-0.175(KC - 1)\}]$$

Where S is the maximum equilibrium scour depth, B is the diameter of the head of the breakwater and is C is the uncertainty factor.

The Keulegan-Carpenter number is defined by the following equation:

$$KC = \frac{VT}{B}$$

Where V is the amplitude of the flow velocity of water at the bed of the section under investigation, T is the wave period and B is the diameter of the head of the structure (Sumer & Fredsøe, 1997). This method of scour prediction can only be used in a marine modelling environment in which waves are present due the KC number, in the case of this project a steady constant flow is applied to the model without wave action.

Some numerical modelling methods can be used in conjunction with physical modelling as a compromise between the two methods. The numerical model can be used to analyse a variety of different variables and scenarios and provide boundary conditions and general flow and material behaviours which can then be used in physical models to assess the scour behaviour in detail (Whitehouse, 2006).

Field data is the third alternative method to numerical and physical modelling and in many cases can be considered a more economic, practical and accurate method of scour investigation, however this cannot be used accurately for future prototypes. Field data can be used to validate numerical or physical modelling to ensure accuracy in its application which theoretically can then lead into prototype testing for future projects when used in conjunction with physical or numerical analysis.

It is worth observing that most records about severe scour problems experienced by structures are often commercially confidential or at least sensitive and will not generally be reported in open literature therefore contributing to the limited published literature (Whitehouse, 1998).

Scour protection

Numerous techniques have been employed to achieve levels of protection and prevention of scour; however their effectiveness is not well documented due to information about the failure of many structures being sensitive. Some of the hard engineering methods in place include; marine mattresses, perforated breakwater walls, extended base slabs, protective aprons, concrete saddles and anchoring with strops and soil anchors. These solutions to scouring are incorporated into the design phase of structures and are present throughout the design life of the structure. Methods for scour prevention or protection that can be included after the construction of a structure include sand bags or grout filled bags, trenching around pipelines and rock dumping, whereas soft engineering solutions include; artificial seaweed, soil improvement, flow energy reduction devices like artificial reefs and vegetation (Herbich, et al., 1984; Whitehouse, 1998; Whitehouse, 2002).

Summary

The review of the literature on scour has been presented in this chapter with the aspects of coastal scour and current research relating to this project being the focus. The experiments conducted as part of this project focus on the effects of water depth, velocity and time on the sediment around a breakwater structure.

Case studies

Introduction

The following chapter concentrates on the two structures; The Falmouth Eastern breakwater and The Mount Batten breakwater. A brief description of the types of structures and roles they play in their environments will be discussed as well as information about the history and stability of the two structures over time.

Description of structures: Falmouth Eastern Jetty

Formally known as the Prince of Wales wharf in the 1860’s the Falmouth Eastern jetty breakwater, located on the Southwest coast of Cornwall England, is a breakwater structure located at the entrance to Falmouth Harbour.

The structure provides important coastal protection to the ship yard and vessels inside. On the breakwater itself is a jetty structure that is used for the mooring of vessels to undergo tank cleaning prior to dry-docking as well as acting as a Marine Oil Terminal for fuel, oil and marine diesel (ThePacket, 2013).

The breakwater stretches roughly 280m into the estuary of the river Fal at its mouth. The river Fal has an average water depth of 3-5m on the east seaward side of the breakwater. The western side of the structure maintains a constant depth of 8m through dredging to accommodate large ships.

Falmouth Harbour and the Carrick Roads, the estuary of the River Fal, are commercially vital to the shipping industry, providing facilities such as cargo handling, dry docks, bunker barges, casualty moorings, underwater services and 24-hour pilotage (EngineeringTimeline, 2013). Located in what is regarded as the third largest natural harbour in the world the breakwater structure provides important protective and economic benefits to the town of Falmouth (Pond, 2007; SuperYachtUK, 2014).

Initial construction of the Eastern Breakwater and the Western Wharf is estimated to have started in 1860 and completed in 1867 with extensions and multiple renovations undertaken following the Second World War. Further improvements to the jetty are scheduled for the latter half of 2016 and include link bridges and new mooring dolphins (ThePacket, 2013).

Following a survey undertaken in 2013 a detailed map of seabed depths was produced, this can be found in Appendix A. With a spring tidal range of 4.6m, large volumes of water travel past the breakwater structure contributing to the scouring effect, other factors impacting the structure would include, currents and manoeuvring ships (Digimaps, 2016). Beyond 10m distance from the structure is the shipping lane that vessels use to navigate into the harbour and docks; this channel is kept at a maintained depth through dredging to improve access to Eastern jetty (CornwallCouncil, 2014).

Following a study undertaken in 2000 by Falmouth Harbour Commissioners, the benefits of dredging the dock basin and approach to Falmouth were highlighted. At the time of the survey a limiting depth of 5.1m was identified in the approach channel which would prevent larger cargo ships from accessing the harbour and docks (FalmouthHarbourCommisioners, 2011). In order to attract the larger shipping vessels and larger volumes of traffic, significant dredging was undertaken in 2013 removing 250,000 cubic yards of spoil from the docks basin (ThisistheWestCountry, 2013). However dredging of approach channels can have an increasing effect on wave energy, localised erosion and have an impact of tidal current speeds, all of which can effect scouring around the base of marine structures (White, 2006).

Description of structures: Plymouth Mount Batten breakwater

The Mount Batten breakwater was constructed in 1881 and is located on the Southwest coast of Devon England in Plymouth Sound. The structure is located at the entrance to Sutton Harbour and provides important coastal protection from the sea to the harbour and the start of the Cattewater (Moseley, 2011).

The breakwater stretches roughly 260m from the outcrop of the Mount Batten peninsula and rises to roughly 2.5m above the waterline. The average water depth of the South side of the breakwater is 1.5 - 2.4m and around 1.3 - 3m depth on the North side with a channel to west which is maintained to a depth of 5.5m through dredging (Digimaps, 2016).

The Mount Batten breakwater benefits from the protection of the main Plymouth Breakwater, and itself provides additional protection from hostile sea states and allows vessels to navigate into Sutton Harbour safely and onwards into the River Plym. As well as providing this vital protection to the surrounding coastline the breakwater has been used for many different activities over the course of its lifetime from being used as part of the RAF air station from 1928-1994 to present-day providing an area for the local population and tourists to go walking and fishing (BlueSoundFishing, 2010; ForcesWarRecords, 2016; Tretheway, 2008).

Before this breakwater was constructed the Mount Batten peninsula was affected by substantial coastal erosion. Before it was in place the Cattewater required annual dredging and maintenance as debris would be deposited during storms affecting the shipping channel. A sea wall was built to protect the peninsula in the early 1600's however it was breached multiple times. Coastal erosion around the Mount Batten peninsula remained a problem and arguably was not effectively controlled until the completion of the main Plymouth Sound breakwater (Moseley, 2011).

The Mount Batten breakwater has been subjected to many storms over the years it has been in place and has undergone multiple restoration phases the most recent being in 2014. During the storm period in which the Dawlish seawall collapse occurred the Mount Batten breakwater along with most of the Plymouth coastline was subjected to extreme weather conditions. This resulted in cracking in the outer walls of the breakwater structure and failure of the ground slab on the promenade in multiple areas (PlymouthCityCouncil, 2014). Reports suggest that the breakwater received some of the most significant structural damage in Plymouth during the severe weather in early 2014 (Waddington, 2014). The storms not only had an obvious physical effect on the breakwater but it was reported to have led to wider economic and environmental impacts following the storm period (PlymouthCityCouncil, 2014).

With a spring tidal range of 4.7m, large volumes of water travel past the breakwater structure contributing to the scouring effect, other factors impacting the structure would include, currents and the propeller wash from manoeuvring ships (Digimaps, 2016). It is notable that at around 22m distance from structure there is a sharp decrease in the depth of the seabed. This is the defined start of the shipping channel which is maintained at a deeper level for large ships. This area is at the edge of Smeaton Pass and Cobbler Channel, both of which are used for navigation of vessels up the Tamar and Plym Rivers.

Preliminary Experiments

Introduction

In order to replicate field results in a laboratory setting it was necessary to design a series of tests that enable a comparison between field and laboratory data. Risk assessments produced for both laboratory work and field data collection work can be found in Appendix B.

The following chapter describes the preliminary laboratory experiments and field data collection undertaken as part of this research project. Initial testing to establish the parameters and limitations of the laboratory equipment was undertaken, this included a sieve sample test. This was undertaken in order to investigate the sediment size to characterise the model seabed for the subsequent testing. Flow speed tests were undertaken to document the maximum output achievable through the apparatus as well as defining the water depth limitations. Field data collection was undertaken to obtain information about the Mount Batten structure in order to reproduce a scaled model in the laboratory.

Sieve test

In preparation for the preliminary experiments a sample of the sediment in the tank was taken, dried in an oven over night and sieved to examine the size of the sediment. The sediment in the tank was constant throughout the tank but the sample was taken from different areas of the tank to ensure uniformity throughout the material.

Figure 2: a) Sieve test apparatus b) Individual sieves showing collected bed material post-test.

The percentages of the sampled sand that passed through the 7 mesh sizes can be found in Table 1.

Table 1: Gradation Test Results for bed material

Sieve Size (mm)	Weight retained (g)	Weight passing (g)	% passing
1.18	5.00	96.70	95.08
0.60	28.10	68.60	67.45
0.43	52.00	16.60	16.32
0.30	13.60	3.00	2.95
0.21	1.50	1.50	1.47
0.15	0.90	0.60	0.59
0.06	0.30	0.30	0.29
0.00	0.30	0.00	0.00

The sieving of the sand concluded that the bed material was fine uniform sand based on the percentage passing for D50 and D90. D50 was found to be equal to 0.52mm and D90 was found to be equal to 0.99mm, this is shown in Figure 3. This sand was used as sediment in the tank to represent the sea bed material.

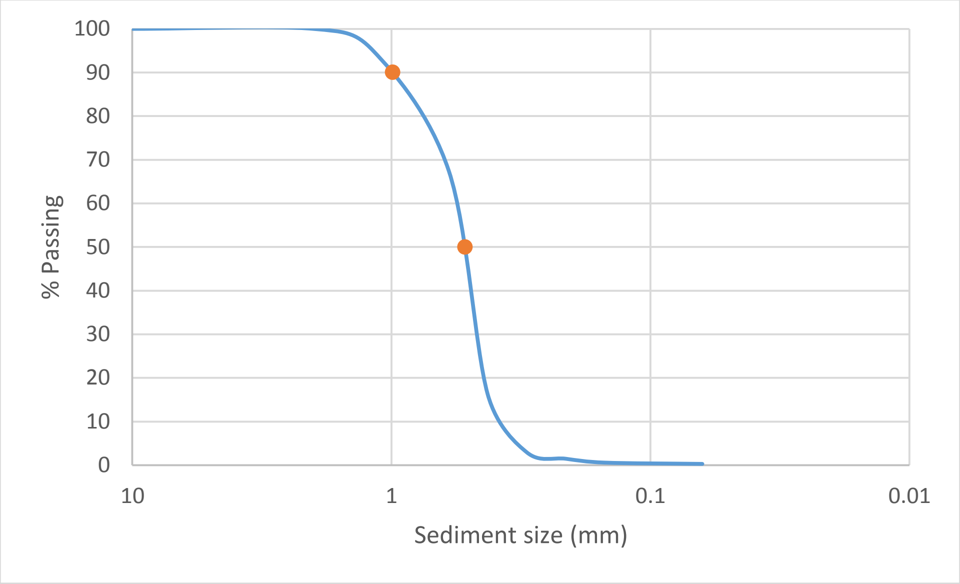

Figure 3: Percentage passing vs sediment size for bed material

The scaled models of the Falmouth and Mount Batten breakwaters were created using physical data collected about the two structures. The data for the Falmouth model was obtained from literature and public access documents about the structure. The data about the Mount Batten breakwater was obtained directly through field data collection.

Testing

Preliminary testing was conducted in an Alborn Rig to investigate the limitations of the apparatus and provide an insight into to the scour depths and patterns achievable using different parameters. This preliminary testing was conducted before the bathymetric survey in order to ensure that the relevant data was collected in the limited time available for that phase of the project. This reduced the likelihood of having to repeat the bathymetric survey at a time when there was significant risk of unsuitable weather conditions. Due to the physical limitations of the Alborn Rig a maximum length of breakwater section that can be used was 40cm and the maximum depth of water achievable was 5.5cm. These dimensions gave the most accurate representation of water, sediment and model interaction. Figure 4 shows t he main elements of the Alborn Rig.

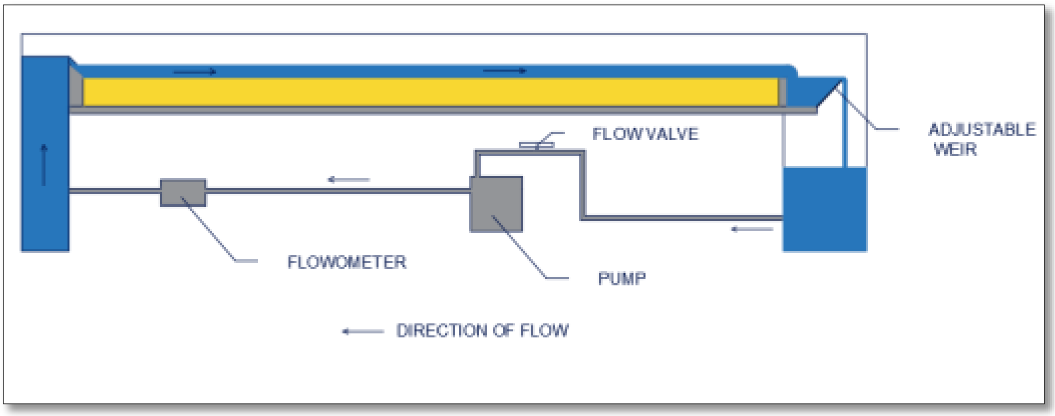

Figure 4: Diagram of Alborn Rig

The Alborn rig consisted of a flume of dimensions 0.62m wide by 2.04m long with an overall depth of 0.2m which includes the 0.06m sediment bed depth. Figure 5 shows the relationship between structure, water and sediment inside the tank.

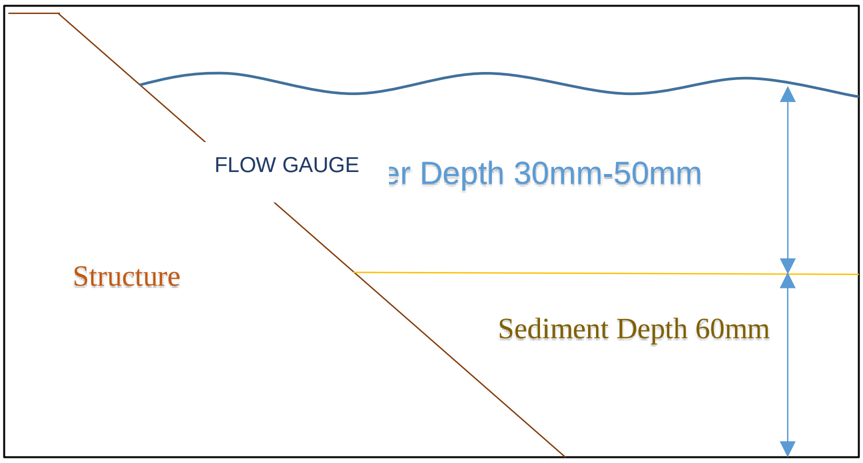

Figure 5: Cross section at end of structure showing sediment layer

Figure 6: Alborn Rig

The Alborn rig shown in Figure 6 has a BomBa PSH Mini 80M 220-230 Volt pump that pumps fresh water through a 48.3mm diameter plastic pipe. An adjustable weir located at the downstream end of the flume acts as a sand trap as well as being used to control the water depth upstream. The level of the sand in the tank was measured using a point gauge and was levelled out to the same level for every test undertaken.

Preliminary experiments were carried out in this tank using basic model breakwaters constructed from steel shapes. Various objects were placed in the tank and the effects that the geometry of the objects had on the sediment in the tank were monitored. This helped in the determination of the equipment parameters and limitations. A range of tests were undertaken to measure different variables and their effect on sediment in the tank, the variables that were changed in each test were water depth, length of breakwater/length of gap between breakwater and tank side, flow rate and time. A basic flow visualisation test was performed using polystyrene balls and recording the flow path they followed.

The breakwater models were embedded in the sand which is 0.06m deep and the water was left to run, the effects on the sediment around the end of the model were observed. Data about the scour holes around the models was recorded using a point gauge that gave a depth reading in millimetres, the depth of the scour holes were determined by comparing the measured value to the observed datum value at which the sand was set.

The time variation tests consisted of running water past a modelled structure at a constant rate. The depth of the scour hole was measured every 5 minutes for up to 40 minutes, the measurement were taken in the same places around the end of the structure using a Perspex grid that was specially made to be used with the point gauge. This gave a good indication of the development of scour over time.

The equipment was adjusted to explore the range of water depths achievable. Due to equipment design, an upper depth limit of 60mm was identified; while the lowest depth was set to 20mm as determined by the scaling effects.Similarly the adjustable weir was lowered to increase the flow in the tank and a max flow rate of 3.7 l/s was achieved at a water depth of 50mm. An initial rough model of 1:1000 scale was used to conduct preliminary testing in the laboratory as shown in Figure 7.

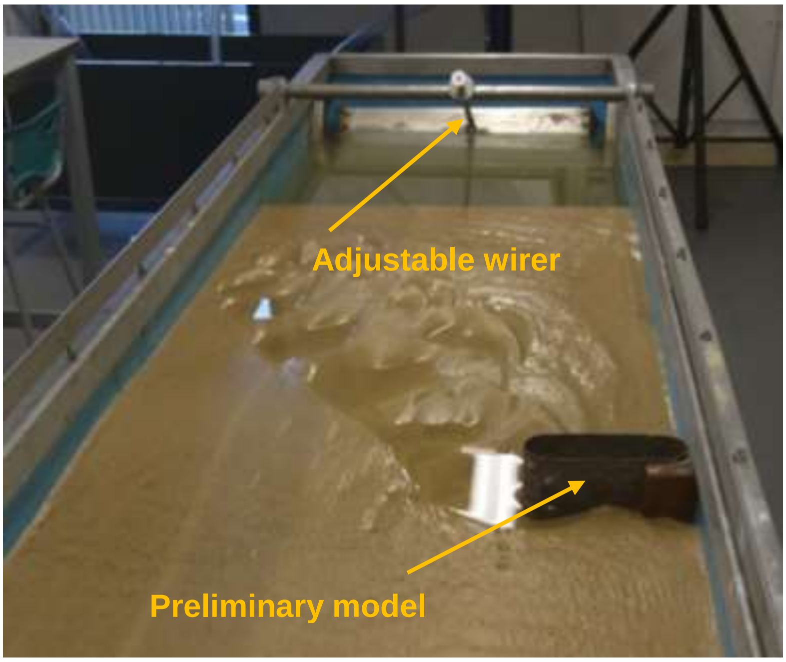

Figure 7: Preliminary model in Alborn tank post equipment limitation testing

Experimental Procedure

The model was embedded in the sediment tank and the sediment was levelled to datum level. The pumps were employed and the water level set using the adjustable weir. The flow gauge valve was set to achieve the required flow rate which was measured using the ultra-sonic flow gauge.

At the start of each test the initial flow rate was recorded. Each 40 minute test was captured on video using a GoPro^{TM} camera. Depth and flow rates were periodically checked to ensure that each test was running accurately.

When the 40 minute period had ended the pumps were turned off and the tank was drained. At this point further images of the sediment bed were captured and scour depth was measured at specific locations using the grid shown in Figure 8. This process was repeated for all the subsequent tests.

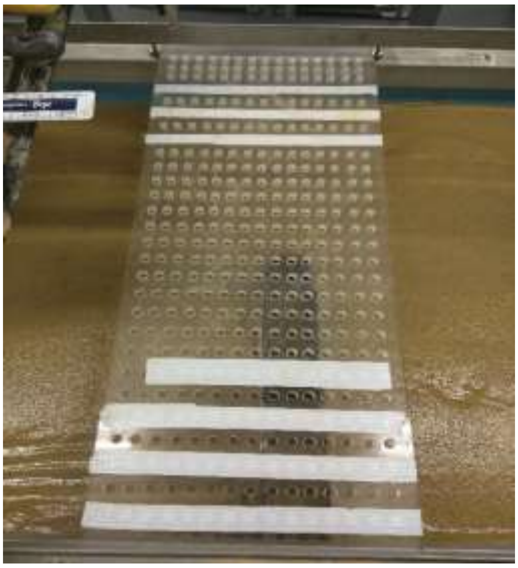

Figure 8: Grid used for measuring spot depths shown over preliminary model

Depth results have been displayed as a cross section of the scour hole indicating the depth profile. Data used in the graphical representations of the depth profiles was collected along the transects shown in the following figures.

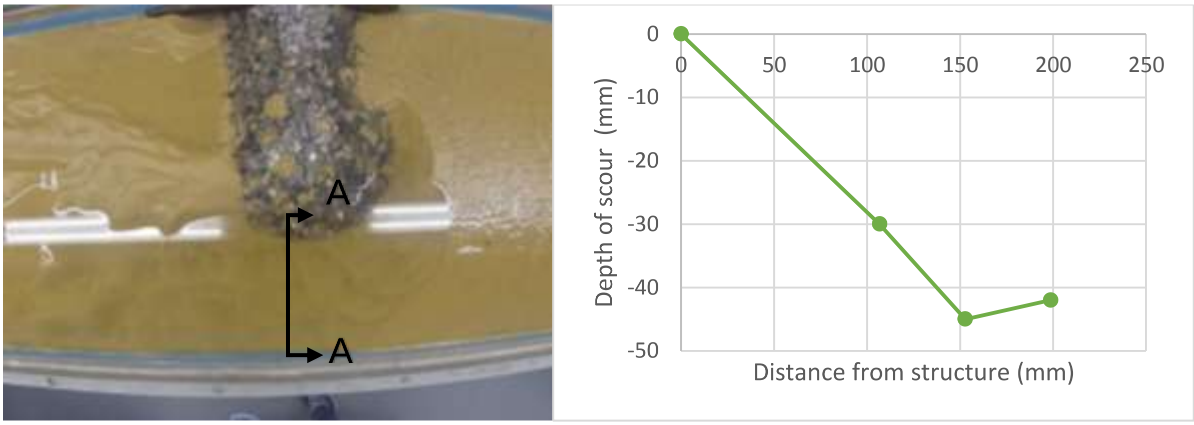

Figure 9: a) Falmouth model plan view of scour post-testing of 50mm water depth with a flow of 3.7 l/s b) transect A-A profile

Figure 9a shows the scour hole around the structure post-test and highlights the line of the scour hole which is represented in Figure 9b.

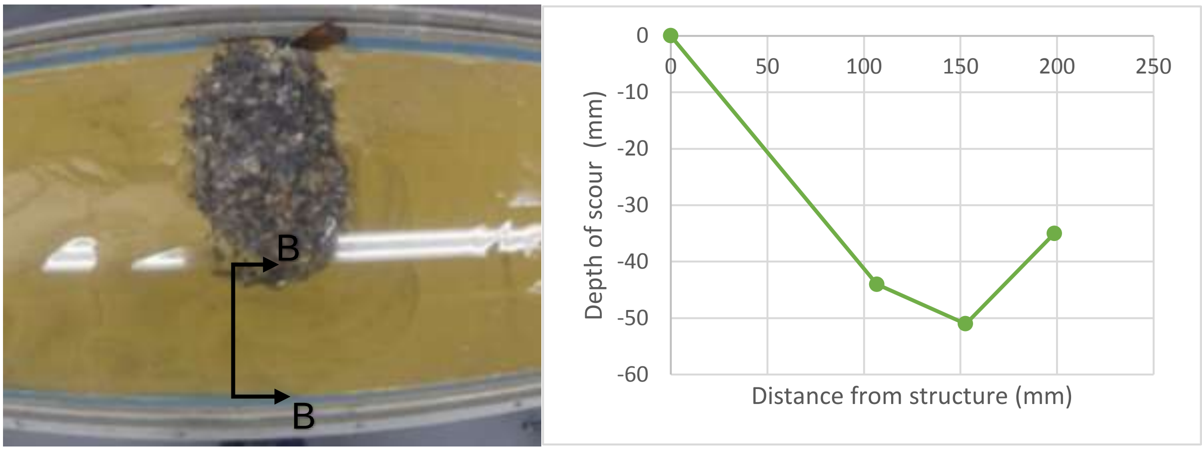

Figure 10: a) Mount Batten model plan view of scour post-testing of 40mm water depth with a flow of 3.7l/s b) transect B-B

Figure 10a shows the scour hole around the structure post-test and highlights the line of the scour hole which is represented in Figure 10b.

Recorded data

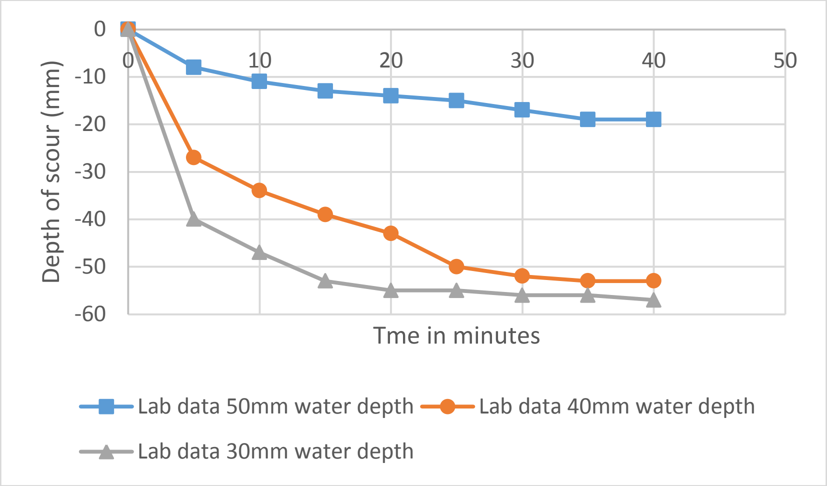

Figure 11: Preliminary scour depth vs time

Figure 11 shows the time taken for equilibrium to be reached during testing of three different water depths; 50mm, 40mm and 30mm. The depths represented in this graph are the maximum depths achieved and show that with a shallower water depth of 30mm the greatest depth of 57mm was obtained, whereas a maximum depth of 18mm was reached with a water depth of 50mm. This indicates a higher local velocity of flow past the structure with the shallower water depth. Both the 40mm and 30mm water depths follow the same trend and indicate that with this increased flow a greater scour representation is achievable. 30mm is the smallest water depth investigated in this experiment due to scaling effects discussed previously. 50mm water depth was the largest depth achievable while a sediment depth of 60mm was maintained across all tests.

Bathymetric data

A bathymetric survey of the Mount Batten breakwater in Plymouth was undertaken. This consisted of the organisation and execution of a water based survey in which a boat was chartered to the Mount Batten breakwater from Sutton Harbour in Plymouth Risk assessment can be found in Appendix B. The purpose of the survey was to collect data about the end of the breakwater in particular the seabed profile, including Eastings, Northings and depths and the flow velocity around the end of the structure. The data was collected using a Garmin GPSMAP 557xs GPS Chartplotter Fishfinder by taking "man overboard" readings which provide precise details of depth, Eastings and Northings of the location (Garmin, 2016). A Valeport current meter was used to measure the flow of the water around the end of the breakwater during mid ebb of spring tide at 10:30am on January 28th 2016.

Flow data was collected by lowering the Valeport current meter over the side of the Plymouth University boat "Dolphin". The black box of the Valeport records data about the depth, flow speed, pressure in Bar, temperature direction, conductivity, salinity and density of the water making it easy for detailed analysis of the results. The results of the test are displayed in Table 2 and are compared to the results obtained in the laboratory in Table 3. Initial test results immediately show that it was possible to model real velocities measured in the field and replicate scaled velocities in the laboratory.

Table 2: Maximum speed data taken from Valeport current meter

Speed; m/S	Direction; deg	Pressure; dBar	Temperature; C	Salinity; PSU
1.811	52.82	0.036	9.064	0.026

Table 3: Model velocity rates compared to field velocity flow rates

Velocities (m/s) in laboratory compared to field				
Flow rate l/s	Model m/s	Scale factor	Scaled m/s	Field m/s
3.7	0.25	$\sqrt{80}$	2.23	1.81
3	0.20	$\sqrt{80}$	1.81	1.81
2	0.13	$\sqrt{80}$	1.21	1.81

Data plots were taken along both the South and North sides of the breakwater as well as the end of the structure and out into the shipping lane to the West of the structure, a data track of the survey can be found in Appendix C, flow rate data was collected from the end of the breakwater as well as in the shipping lane and on the South side of the structure for comparison. A detailed analysis of both the Valeport current meter and the Garmin chartplotter data was performed in Microsoft Excel.

Model calculations

Following the collection and analysis of data from field and laboratory experiments scaling factors for the two models have been defined. Table 4 shows the model scaling factor used to determine the flow speed needed for scaling consistency.

***Table 4** Froude scaling for both models*

Flow Froude scaling (m/s)			
	Prototype	Model scaling factor	Model
Falmouth	0.6	$\sqrt{100}$	0.06
Mount Batten	0.4	$\sqrt{80}$	0.044

***Table 5** Symmetrical scaling for both models*

Water depth symmetrical scaling (mm)			
	Prototype	Model scaling factor	Model
Falmouth	5000	1:100	50
Mount Batten	4000	1:80	50

Table 5 shows the model scaling factor used to define the dimensions of the two models. Detailed drawings of the scaled models can be found in Appendix D.

Two scaled models of structures were used, each based on a real structure and scaled accordingly to be used in the Alborn Rig. The first structure to be tested was the 1:100 model of Falmouth Eastern jetty, the second was a 1:80 model of the Mount Batten breakwater in Plymouth. The scale of models used in the studies discussed previously varied from 1:40 and 1:50 used by Irie and Nadaoka (1984), 1:20 used by Shi-Leng (1981) and a 1:7.5 scale model used by Fowler (1992). This range of model scale used much larger than the scale that can be replicated in the Albion Rig and therefore a scale of 1:80 and 1:100 was chosen.

Froude scaling and symmetrical scaling were used to produce a model of the Mount Batten breakwater at a 1:80 scale and a model of the Falmouth breakwater at a 1:100 scale shown in Figure 12a and 12b.

Figure 12: a) Plan view of Falmouth and Mount Batten models (L-R) b) Elevation view of Falmouth and Mount Batten models (L-R)

Both the Falmouth and Mount Batten breakwater models made for this project were comprised of a dense foam core that geometrically represents the core layers of the breakwaters. Two layers of aggregate covered the foam core, one layer of 20mm and one layer of 10mm. The aggregate layers are attached to the foam cores using a silicone sealant which allows flow of water around the individual stones but provides a strong hold and prevents the stones being removed during testing.

Summary

A description of the preliminary laboratory experiment and field data collection process has been presented in this section of the report. The laboratory apparatus limitations and characteristics have been evaluated and have been used to develop the hydraulic model tests presented in Chapter 5.

Experimental Study

Introduction

The following chapter documents the experimental tests undertaken on the two model structures previously discussed. The experiments preformed include effect of the depth of water on scour, the effect flow velocity has on scour and the progression of scour over time and the time taken to reach equilibrium.

Model calculations

The experiments were split in to two main testing groups. The first group of tests consisted of testing the effects of water depth on the sediment at the end of the structure, the second group of tests involved just the Mount Batten model, different parameters were changed and investigated including the flow velocity and time intervals .

All of the tests undertaken in this study have been conducted to investigate the effects of different parameters on the scouring process in order to determine the accuracy of small scale modelling for research into this complex subject.

Experimental characteristics

The structures were placed in the flume at 102 cm which is half way along the length of the flume. This was to ensure that any turbulence experienced from the pumps did not affect the scouring process of the experiment. As shown in Figure 13 the upstream half of the flume depicts smooth unsettled sediment which indicates little to no interference from the pumps. This was to ensure clearwater scour was observed.

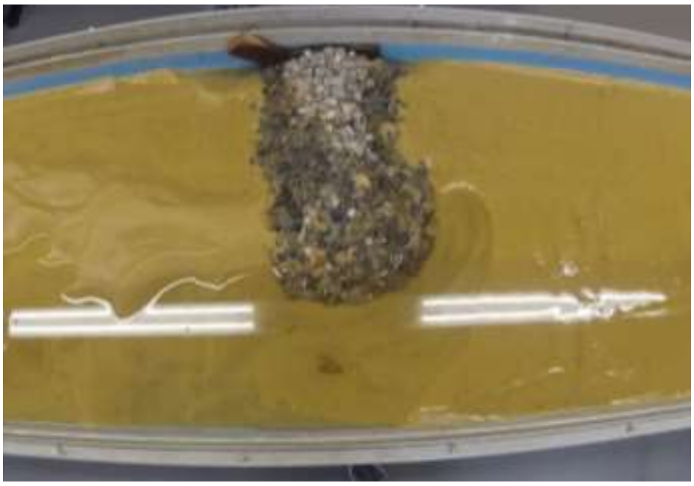

Figure 13: Image of Falmouth model post-test indicating smooth upstream bed material

A Go-Pro™ camera was set up on a boom over the flume and positioned above the structure to allow for filming of the test. This allowed replay of the testing and also made it easy to identify the exact moments that different processes occurred. For example during the first group of tests the Falmouth structure failed due to the low mass of the model, ingress of water underneath it caused the model to uproot from the base of the flume. This was the unexpected result of the severity of scour on this structure.

Figure 14: Falmouth model fail

Figure 14 shows the model has been lifted and exposed the wooden base underneath. The model its self weighs 6.58Kg and was subject to 40mm of water at a flow rate of 3.7l/s, the behaviour of the model was unexpected when considering the weight of the model compared to the water depth, however this problem was remedied by placing paving bricks on top of the model to weigh it down. This was an acceptable solution to the problem as in this case the point of interest is the scouring occurring around the structure and not the structure behaviour itself. The results from this particular test were omitted and the test was repeated.

The parameters that have been investigated through the tests undertaken as part of this study include; water depth, water flow velocity and time. The reason for this is to gain further understanding of sediment behaviour under different conditions and to examine the depth and area of the scour produced around the structures. The parameters under investigation have been highlighted through review of current literature around the subject in question, as referred to in Chapter 2, and have been quantified through preliminary testing in the laboratory.

Procedure and results

The procedure for the first group of tests on the models of Falmouth and Mount Batten is a replica of the preliminary tests undertaken on the preliminary model discussed previously.

The second group of tests consisted of only using the Mount Batten model and varying the flow rate of the water by adjusting the flow valve, shown in Figure 4, and noting the effects this had on the depth and area of the scour. A test was also undertaken where the evolution of the scouring process was documented over a 40 minute block of time at regular 5 minute intervals.

A root mean square deviation method was used to measure the accuracy of the laboratory tests using the following equation.

$$RMSD = \frac{1}{N}\sum_{i=1}^{N}(P_i - M_i)^2$$

Where N is the number of data plots, P_i is the field data, M_i is the laboratory data at an instance i = 1 (Holmes, 2000).

Recorded Falmouth model data:
A series of tests performed using the Falmouth model with different water depths was undertaken, the results are displayed in Table 6.

Table 6: Recorded data from Falmouth Model water depth experiments

Test	50mm water depth	40mm water depth	30mm water depth	
Q (m^3/s)	0.00369	0.0037	0.00373	Falmouth Model
V (m/s)	0.14	0.24	0.38	
d (m)	0.05	0.04	0.03	
Max scour depth (m)	0.035	0.040	0.051	

Where Q is the water flow rate, V is the velocity and d is the water depth.

Recorded Mount Batten model data:
A series of tests performed using the Mount Batten model with different water depths was undertaken, the results are displayed in Table 7.

Table 7: Recorded data from Mount Batten model water depth experiments

Test	50mm water depth	40mm water depth	30mm water depth	
Q (m^3/s)	0.00371	0.00372	0.00369	Mount Batten Model
V (m/s)	0.16	0.25	0.41	
d (m)	0.05	0.04	0.03	
Max scour depth (m)	0.02	0.045	0.054	

The recorded data from the flow velocity experiments on the Mount Batten model are presented below in Table 8.

Table 8: Recorded data from Mount Batten model flow velocity experiments

Test	40mm water depth	40mm water depth	40mm water depth	
Q (m^3/s)	0.0037	0.003	0.0021	Mount Batten Model
V (m/s)	0.25	0.20	0.13	
d (m)	0.04	0.04	0.04	
Max scour depth (m)	0.044	0.03	0.01	

The data recorded from the scour development over time experiments has been presented below in Table 9. Note that sediment datum level is at 140mm.

Table 9: Recorded data from Mount Batten model scour depth over time experiment

Time (minutes)	Recorded sediment depth (mm)	Depth of scour (mm)	
0	140	0	Mount Batten Model
5	105	35	
10	95	48	
15	92	50	
20	88	52	
25	82	58	
30	80	60	
35	78	62	
40	78	62	

Summary

Descriptions of the experiments undertaken as part of this research project on scour have been presented in this chapter. The results of the investigation of water depth, flow velocity and time parameters have been presented and are discussed in the following chapter however it can be seen from the results above that scour has successfully been replicated within the laboratory to an acceptable level of accuracy.

Results

Introduction

The following chapter presents the results found from the experimental studies discussed in Chapters 4 and 5. The scour dimensions due to water depth experiments are presented and discussed for each model, the transect of data used in the graphical plots is the same as previously shown in Chapter 4 section 4. The laboratory results are then compared to the field data conducted and discussed. This leads to the discussion and presentation of how the area of scour differ due to the depth of the water.

The recorded scour hole dimensions from the three flow velocity experements are presented in one graphical representation. The scour development over time experiment is shown and discussed in this chapter. Clearwater scour was achieved in all preliminary and final experements.

Effects of water depth on scour events

Falmouth model:
A graphical representation of the maximum recorded scour depths in a cross sectional tangent of the scoured area at the end of the structure is shown below in Figure 15.

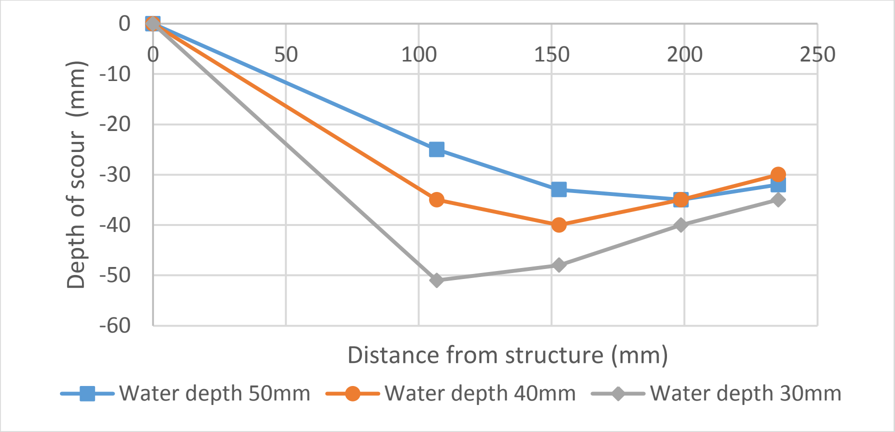

Figure 15: Graphical representation of scour depths from the end of the Falmouth model for varying water depths.

The end of the structure is located at 0mm, all measurements are taken from the end of the structure. The maximum depth of scour that was recorded i achieved when a water depth of 30mm was used whereas the smallest scour depths achieved are that of the 50mm water depth, this implies that with a smaller water depth the scour depths occurring will be deeper, this is consistent with the idea that the lower the water depth the faster the water flow past the structure will be. This is due to the pump in the Alborn rig pumping at a continuous flow rate of 3.7l/s.

Mount Batten model:

A graphical representation of the maximum recorded scour depths in a cross sectional tangent of the scoured area at the end of the structure is shown below in Figure 16.

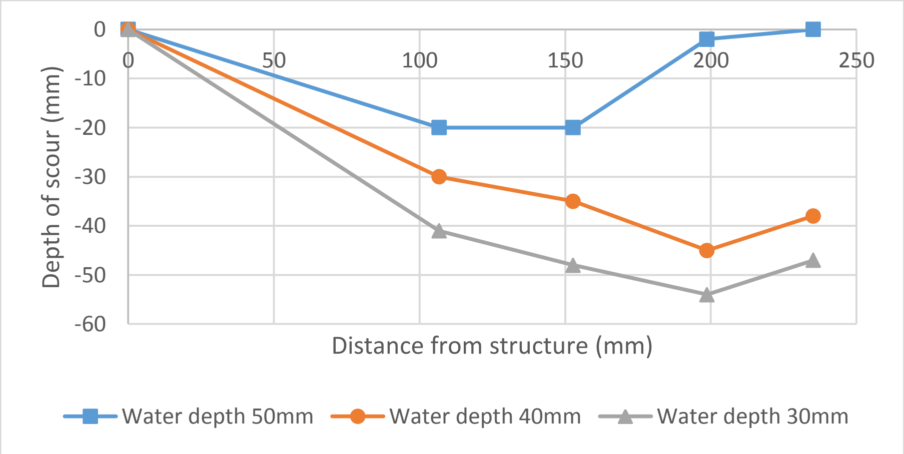

Figure 16: Graphical representation of scour depths from the end of the Mount Batten model for varying water depths.

Similar to the results of the Falmouth model the maximum scour depth achieved was with a water depth of 30mm and the least scour was achieved with a water depth of 50mm implying an increase in scouring effect in shallower water.

Field data

From the survey information collected a plot of the sea bed profile against the distance from the Falmouth breakwater in a north easterly direction could be created. Where 0 is chart datum.

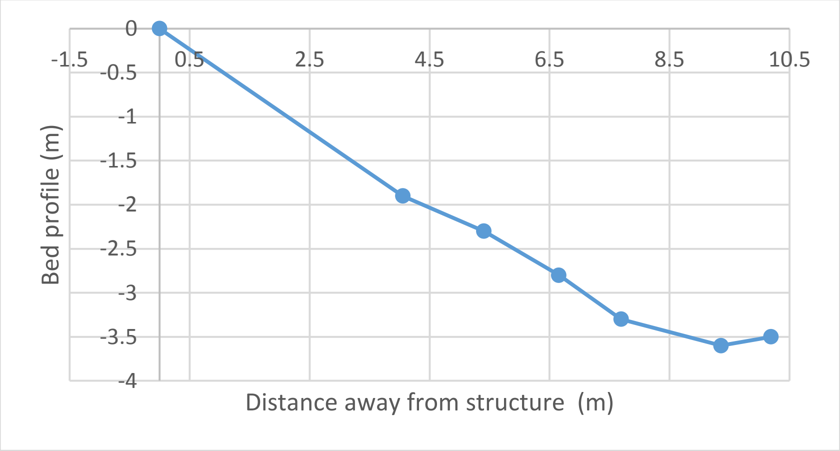

Figure 17: Graphical representation of the seabed depths at the end of the Falmouth Breakwater data taken from survey found in Appendix A

Following the bathymetric survey undertaken for this project in January 2016 data about the seabed depth around the structure was collected and a depth profile of seabed at the western end of the breakwater was produced with depths measured from 0 as chart datum.

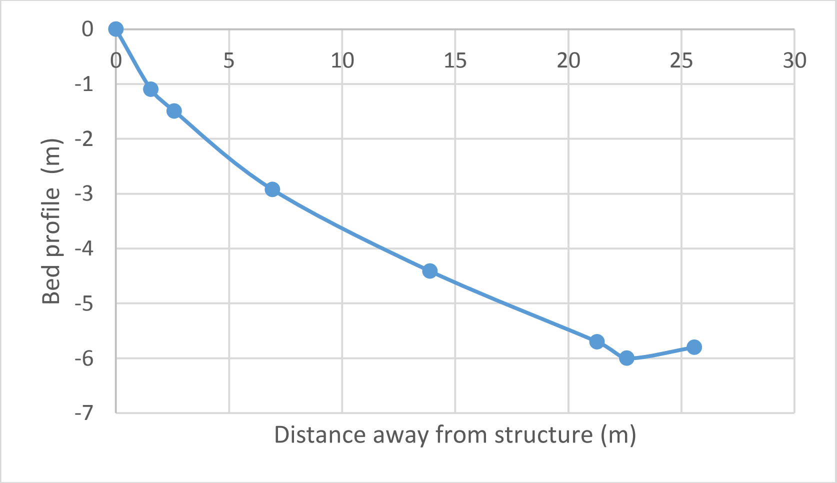

Figure 18: Graphical representation of the seabed profile at the end of the Mount Batten breakwater

Figure 18 shows the drop in seabed level at the end of the breakwater where 0 depths represent 4.1m below the waterline.

Comparison with field data

The measured depths of the scour from the three laboratory tests have been scaled up to real life scale, also known as prototype, and compared with the field data collected to evaluate which water depth gives the most suitable representation of scouring. Table 10 presents this data comparison between field and laboratory data. This stage shows that it was possible to reach a prominent correlation between field and lab data.

Table 10: Scaled depth of laboratory data displayed alongside field data

	Depth (m)			
Distance from structure (m)	Field Depth	50mm Water Depth	40mm Water Depth	30mm Water Depth
0.00	0.00	0.00	0.00	0.00
4.06	1.90	1.25	1.85	2.55
5.41	2.30	1.58	2.03	2.48
6.66	2.80	1.65	2.15	2.40
7.70	3.30	1.71	1.90	2.25
9.36	3.60	1.75	1.75	2.00
10.19	3.50	1.60	1.50	1.75

Falmouth model:

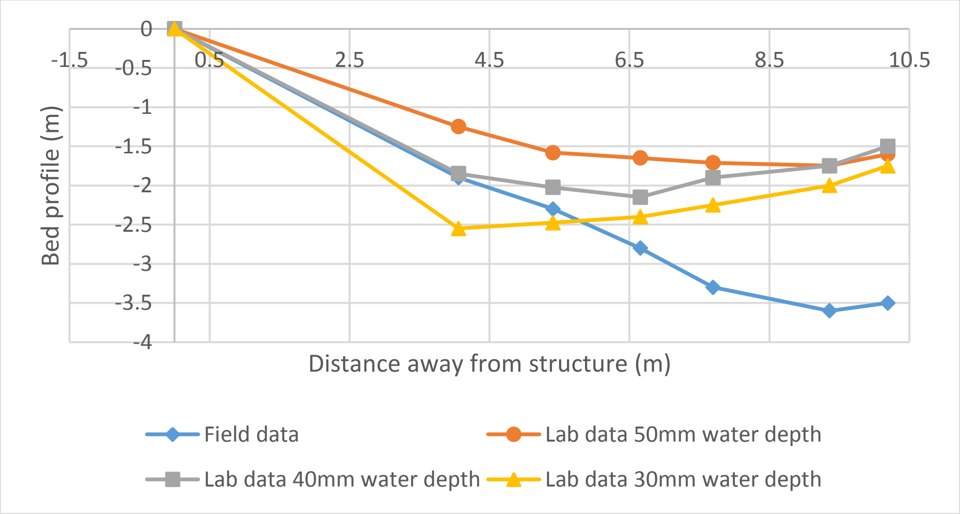

Figure 19: Falmouth field data and lab data comparison

Figure 19 shows a comparable trend between the laboratory experiments and the field data.

Of the three laboratory results the 50mm and 40mm water depths follow the trend of the field data the best and of these two values the closest is 40mm water depth. The 30mm water depth does not follow the same trend as the field data which could be due to the increase in local flow past the structure due to the low water level.

A RMSD analysis was performed on the laboratory data to determine the accuracy of the results. Table 11 shows that the 30mm water depth has the smallest average deviation in distance from the field data however from Figure 19 shows that this could be due to an over correction in the differences due to the large depth at 5.5m away from the structure and smaller depth of 2m at 10m away from the structure.

Table 11: RMSD analysis on Falmouth laboratory data

	50mm Water Depth	40mm Water Depth	30mm Water Depth
Average deviation (m)	1.54	1.41	1.21

This analysis shows that a water depth of 30mm gives the most apt representation of scour around a modelled structure of Falmouth structure as the RMSD tends to 0 with the convergence of the curves.

Mount Batten model:

Table 12: Scaled depth of laboratory data displayed alongside field data

	Depth (m)			
Distance from structure (m)	Field	50mm Water Depth	40mm Water Depth	30mm Water Depth
0.00	0.00	0.00	0.00	0.00
1.54	1.10	0.70	1.00	2.00
2.57	1.49	1.00	1.60	3.50
6.92	2.93	2.00	3.00	4.10
13.88	4.41	2.00	4.10	5.20
21.28	5.70	0.20	4.60	5.40
22.58	6.00	0.10	4.40	5.20
25.58	5.80	0.00	3.80	4.50

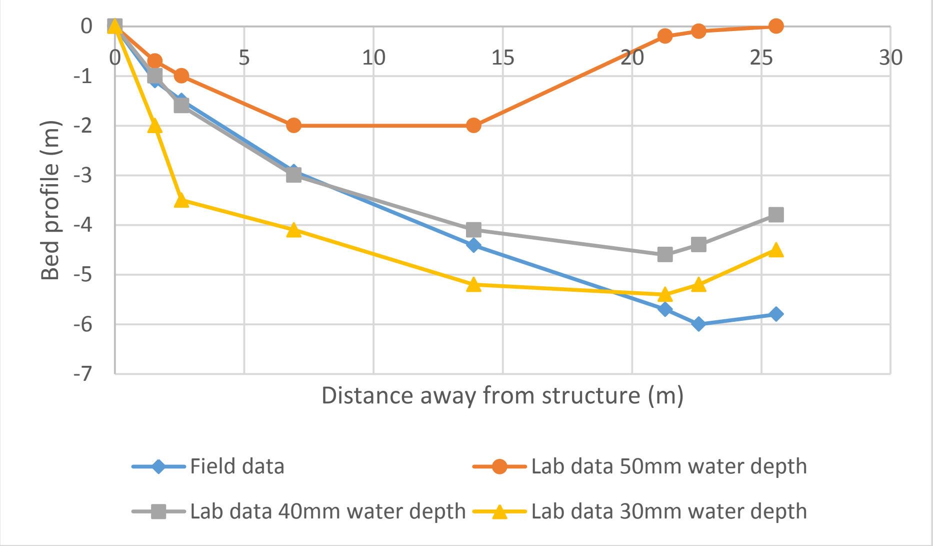

Figure 20: Mount Batten field and lab data comparison

Figure 20 sows a close similarity to the field data with a comparable trend between the results of water depth of 40mm and the field data. The 30mm water depth plot follows the trend but cannot be called a close representation and the 50mm water depth plot does not accurately represent the field sea bed profile, suggesting that a water depth of 40mm gives the most fitting representation of scour around this structure.

An analysis of the accuracy of the tests was conducted for the Mount Batten structure laboratory data using RMSD equation and provided the results displayed in the table below.

Table 13: RMSD analysis on Mount Batten laboratory data

	50mm Water Depth	40mm Water Depth	30mm Water Depth
Average deviation (m)	4.60	1.22	1.36

The results clearly indicate that the 40mm water depth gave the best correlation with the lowest average deviation between the field data plots indicating a good correlation and representation of the sea bed profile achieved. Therefore, the optimum test conditions have been identified and the following experiments undertaken are defined using this water depth parameter.

Effects of water velocity on scour area and depth

The parameter of flow velocity was investigated using the Mount Batten model using a fixed water depth of 40mm which was determined to be the most appropriate solution following the previous experimentations on water depth. The three different velocities investigated include 0.25m/s, 0.20m/s and 0.13m/s. The areas of scour were measures using the dimensions highlighted in Figure 21.

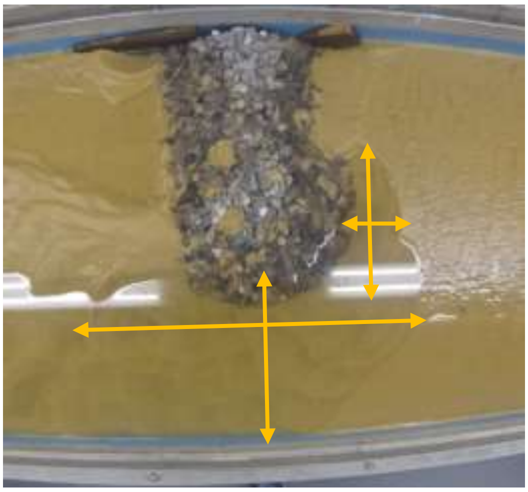

Figure 21: Location of where measurements were taken for area of scour

The maximum areas of the scour holes were measured after 40 minutes and are displayed in Figure 22.

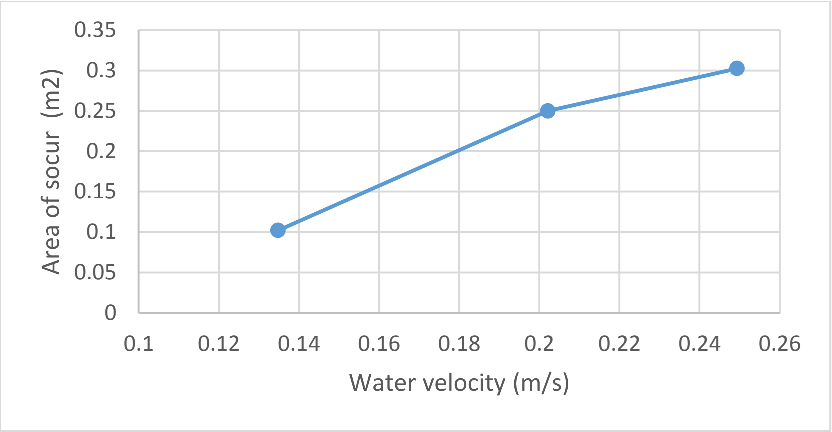

Figure 22: Mount Batten area of scour vs water velocity

It is clear that there is a relationship between the depth of the scour area and the increase in water velocity. This is to be expected since increased turbulence usually follows increased velocity (Hamill, 2011).

Figure 23 presents the data collected about the relationship between depths of scour and water velocity.

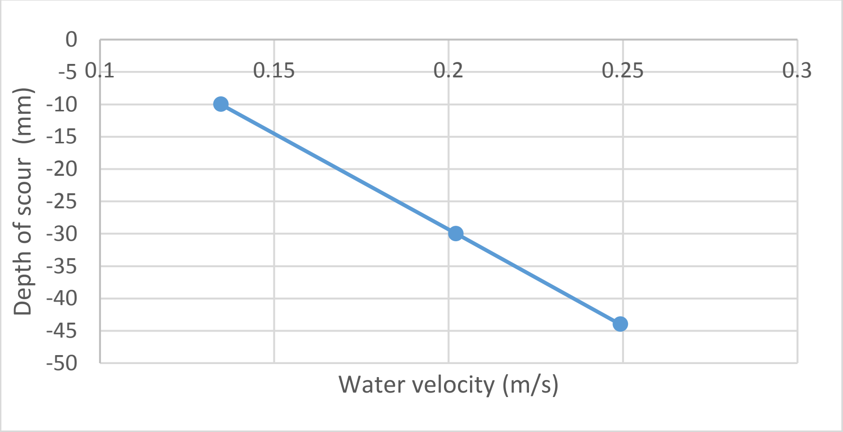

Figure 23: Mount Batten scour depth vs water velocity

As can be seen from the graph above there is a directly proportional relationship between scour depth and the velocity of the flow. The maximum scour depths recorded increase as the velocity of the flow increases meaning the deepest scour occurs as water velocity increases to 0.25 m/s.

Effects of time on scour depth

An experiment looking into the evolution of scour was undertaken on the Mount Batten model using a constant water depth of 40mm. The purpose of this experiment was to understand how scour develops over time and to investigate the point at which equilibrium is achieved if at all. Figure 24 presents the findings of this experiment.

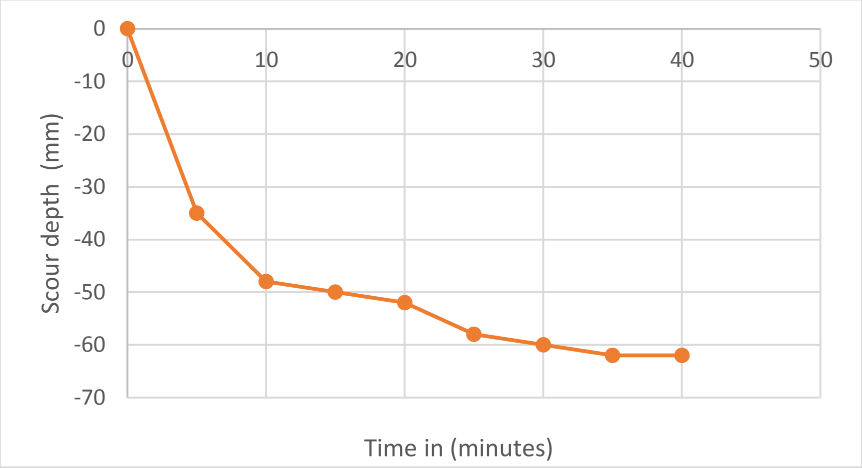

Figure 24: Mount Batten scour depth vs time

The scour depth was measured at the edge of the structure where the deepest scour had been observed in previous test. The profile of this plot indicates that rapid scouring of the sediment occurs between 0-10 minutes and slowly evens out until it tends to an equilibrium state at 40 minutes. This is in keeping with the equilibrium theory discussed in Chapter 2. The time taken for this model to reach equilibrium equates to approximately 6 hours in the field applying a Froude scaling factor of $\sqrt{80}$, which is in keeping with a study undertaken by (Irie & Nadaoka, 1984).

Summary

The two models built for this project have been extensively tested over a period of six days with the intention of investigating the effects of different variables on scour around the models. The results presented show that it is possible to replicate scour at this scale. Previous studies undertaken have tested models on scales of 1:40 and 1:50 with satisfactory results (Irie & Nadaoka, 1984), this project has proved that it is possible to use models of 1:80 and 1:100 and maintain a level of accuracy suitable for preliminary stages of design projects.

The experiment looking into the depth of scour with a variable water depth shows that for all tests a good representation of scour was achieved. Both models show a drop in the sediment level and an increase as the distance from the structure increases. This shows that scour is present however as sediment returns to the datum point on only one test, the 50mm water depth for Mount Batten, it indicates that the distance between the structure and the edge of the tank is not sufficient to incorporate the extent of the scour hole.

The experiments undertaken have highlighted that for a water depth of 30mm a more realistic bed profile was achieved for the Falmouth model compared to 40mm water depth which gives the closest representation for the Mount Batten model. This analysis was undertaken using RMSD equations with the closest average deviation tending to 0.

A time scour evolution experiment was undertaken showing that, with a water depth of 40mm and a flow rate of 3.7l/s, equilibrium scour state could be achieved within 40 minutes.

Discussion

Results discussion

Different water depths in the model produced different scour depth results. Since flow rates were held at a constant 3.7l/s this closely models the situation of tides in the field. The different water depths are representative of the drop in tide where the flow rate remains constant but the velocity increases due to the reduction of area (Whitehouse, 1998). Due to this relationship shallow water in the model produced deepest scour for both models.

Modelling at a depth of 30mm for Falmouth and 40mm for Mount Batten produced a scour profile most similar to that found in the field. This difference between is explained by the different sea water depths at each of these breakwaters.

As water velocity increases the area of scour also increases due to the relationship of Q=VA previously discussed (Whitehouse, 1998). Higher velocities will produce greater scour area until equilibrium is reached; this supports the findings of (Harris, et al., 2010).

Over time the scour depth increased to the point of equilibrium at all 3 water depths in the model. In the experimental condition where depth was set at 40mm this occurred after 40 mins. This equates to approximately 6 hours in the field applying a Froude scaling factor of $\sqrt{80}$, which is in keeping with a study undertaken by (Irie & Nadaoka, 1984). Due to limitations of equipment a unidirectional flow was achievable in the Alborn Rig and therefore this model was unable to represent the effects of the tide however, as equilibrium was achieved within approximately 6 hours, this model has the potential to be developed to represent the 12 hour cycle of tidal effects.

The development of scour depth over time closely represents the equilibrium profiles discussed by Breusers (1972), Fredsøe and Sumer (2002) and Harris, et al. (2010).

Implications of the results

As a result of the completion of the experimental investigations performed as part of this project, a conclusion has been reached, which is that this method of investigation is a valid and accurate technique of modelling scour at this scale in comparison with similar published investigations with larger models. Modelling on this scale provides useable results in a reasonable time frame at significantly less cost than other ways of collecting data. The bathymetric surveys reviled that there was no visible scour pits at the end of either structure. This was an unexpected outcome which emphasises the complexity of coastal scour, it is likely that variables such as such tides, bidirectional currents, interaction with other structures and turbulence from marine vessels is accountable for the absence of the usual scour patterns for either structure. However the data collected was valuable in developing the test methodology and will be helpful in future investigations of scour.

Testing of structures on a scale of this nature is cheaper than the widely used large scale modelling that is conducted in specialist facilities. This can provide designers, local authorities and researchers with the means of testing projects during preliminary stages on a practical basis without significant investment in time and money and can provide useful results which are a basis for further more complex study at further stages of a civil engineering project. This was as discussed by ICE

(1985) in which they highlighted the effectiveness of model testing as a method of studying scour in the design stage of a project.

Limitations

Whilst there are some limitations with respect to this project they are mainly defined by the characteristics of the Alborn Rig as only uniform flow at a constant depth is achievable using this equipment. The uniformity of the flow could be used to model the influx of a tide however and this method of testing could be used for river modelling. The use of the Alborn Rig in this project shows, that with future research and development, this method of testing could prove to be beneficial. There are some limitations to the modelling of tides, currents or storms using this method but aspects of these variables could be investigated in future. The bathymetric survey conducted around Mount Batten breakwater was time constrained due to availability of the vessel therefore data about the bed profile was taken at mid ebb on a spring tide. Conducting a continuous bathymetric survey over the course of a tide could develop the Mount Batten model further. The Falmouth model experiments could be refined further with a bathymetric survey undertaken specifically for this project.

Recommendations for future work

The recommendations for future work arising out of the research conducted on scour around coastal structures could include; a computational model of the scour around the two structures relating to the parameters defined in this study, a further investigative study into the effects of additional variable parameters affecting scour such as the angle a structure sits in the flow, the shape of the end of the structure and bed material. All of these parameters could be further investigated in conjunction with results obtained from this project. Other possible investigations include the relationship between experimental laboratory data and predicted structural behaviour in defined situations such as rising sea levels as they affect existing structures and a similar examination could be undertaken for live-bed scour or non-uniform bed material.

There are many different variables that could be introduced and evaluated with the purpose of developing the accuracy of hydraulic modelling on this scale further.

Conclusion

Summary of content

The aim of this project was to obtain a deeper understanding of the process of scour in the marine environment by conducting a research project around aspects of the subject and to investigate the relevance and accuracy of scaled model test techniques as applied to this area of study. The research undertaken as part of this project about scour around coastal structures included a desk study, field work and laboratory work.

A literature review of current and available information about scour and the parameters that affect the process was undertaken including a review of the prediction methods currently used and preventative design features for scour.

A bathymetric data survey of the Mount Batten breakwater was undertaken and information about the structure was used to produce a model to a 1:80 scale. A model of the Falmouth breakwater to a scale of 1:100 was also produced. Various testing of the parameters affecting the scouring effect were investigated and analysed with the intention of refining the scaling for the two models. The limitations and capabilities of the laboratory equipment were assessed during preliminary testing and used to define the final experimental parameters. The final experiments conducted investigated the effects of changes in various parameters on scour at the end of a coastal structure. The parameters tested included water depth variations, flow velocities and time evolutions. The results were compared to the field data collected and an analysis of the accuracy of the results was conducted and commented upon.

Conclusion of project

The water depth, flow velocity and time evolution experiments highlighted the effects each had on scour holes at the end of a structure and showed that it is possible to replicate scour profiles at this scale. The experiments conducted using the Alborn Rig and small scale models indicated a desirable water depth of 40mm to achieve the most realistic scouring patterns which correlated closely to field data. The scour information recorded for the increasing velocity of flow showed an increase in the size of the scour hole as well as an increase in the depth. The comparisons drawn between the laboratory and field data highlights the variations in bed profiles between the data. Field data for both Falmouth and Mount Batten show a profile that reaches marginally deeper scouring depths than the laboratory tests however it should be noted that well defined and well developed typical scour pits were not observed in the field. These variations between laboratory and field data are expected as there are multiple variable parameters that have not been all accounted for in the experiments conducted as part of this research project.

Significance of the conclusions

The importance of recognising and understanding the impact of scour and the behaviour of structures affected by the process has been highlighted in the literature review. The scouring that has been observed throughout the various experiments show the impact that the environment can have on a structure and the secondary effects a structure may then have on its immediate local area. The similarity between the laboratory and previous documented investigations shows sufficient promise for it to be claimed that this method of testing could become an important stepping stone in the design and development of future coastal structures projects as well as a tool in the review of current structures and their behaviour in hostile conditions. While typical scour is not always present at coastal structures this project has shown modelling on this scale has represented the sea bed profiles closely.

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