3D ASSET DATA CAPTURE TO EFFECTIVELY INFORM DAMAGE ASSESSMENT AND REPAIR DESIGN OF ROCK ARMOURED BREAKWATERS

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Three-dimensional (3D) data capture is increasingly becoming more accessible and cost effective, and is now widely used as a tool for the monitoring and maintenance of coastal and maritime assets. Specific to rock armoured breakwaters, 3D data capture in the field prior to and after a storm event can provide an exceptional basis to more accurately inform the need, extent and design of repairs compared to other less data rich methods. Despite this, there remains significant further investigation and design consideration to define an effective repair strategy and estimate the armour quantities required.

This paper outlines the benefit of regular monitoring and data capture for monitoring and maintenance of rock armoured breakwater and revetment assets and the associated limitations of the use of point cloud data by asset owners. It describes a number of lessons learnt from utilising bathymetric and topographic point cloud data to assist in the assessment of damage, design of repairs profiles and the quantification of repairs for these. A relevant case study is presented involving the design of major repairs for a number of rock armoured coastal assets in Queensland damaged during a single storm event. The project specified that the repair design shall return assets to a like-for-like level of service as a minimum which required an accurate understanding of the response of the assets through the event. The analysis of detailed pre- and post-event 3D survey data allowed a repair design that targeted the efficient use of existing rock armour to minimise costs, while mitigating some legacy issues introduced over numerous previous repair and upgrade campaigns. The significant benefits demonstrated by this example and others suggests that coastal asset owners should consider incorporating regular 3D detailed data capture of their critical assets to best inform a post-storm damage recovery strategy should this eventuate.

Introduction

Three-dimensional (3D) data capture has become increasingly accessible and cost-effective and is now widely used as a tool for the monitoring and maintenance of coastal and maritime assets. Specific to rock armoured breakwaters, 3D data capture prior to and after a storm event can provide an exceptional basis to more accurately inform the need and optimise the extent and design of repairs in comparison to other less data rich methods such as visual interpretation or 2D surveys. This paper specifically reflects assessment and repairs for rock armoured breakwaters however, the techniques and method could similarly be applied for the design of asset upgrades and concrete armoured breakwaters.

3D data capture methods typically culminate in a high-resolution point cloud. This can be achieved through laser or sound ranging (LiDAR or SoNAR), or photogrammetry techniques. Point clouds across different time stamps can then be digitally compared to identify changes to a structure. This enables assets owners, managers or designers to obtain very accurate insight into the performance of a structure including areas of susceptibility and potential mechanisms of failure. Similarly, should damage occur, comparison of point clouds can provide a robust quantitative basis for a business case to repair the asset.

This paper will first outline the benefits of regular monitoring through 3D data capture in comparison to traditional approaches. It will describe the outputs of a case study where pre- and post-storm event 3D point cloud survey data was utilised to assess the extent of damage to rock armoured structures and will present how this assessment provided an invaluable basis for defining the scope of repair works and informed effective repair design. Further, the paper will demonstrate through the case study how having accurate 3D data can be used to effectively quantify, procure and manage the construction phase, and outlines limitations and lessons learnt in applying this process.

Benefits of 3D Data Capture

There are many methods to assess and quantify the extent of damage to rock armoured structures. Historically, this may have included physical visual inspections, comparison of photos and aerial images, diver surveys and comparison of two-dimensional (2D) terrestrial and bathymetric surveys. A combination of these methods was often employed to gain a relatively inaccurate and subjective primary assessment of actual damage, combined with a comparison to the nominal relative eroded area for the Van de Meer equation (S_d) to empirically estimate the theoretical damage. More recently the comparison of point-cloud topographic and bathymetric survey data has enabled a more accurate primary damage assessment to ultimately determine a percentage of damage relative to the Van de Meer coefficient. Comparison of point cloud data can provide an accurate representation of armour displacement and holistic structure movement and can provide justification for effective repairs.

Particularly relevant to this paper is the initiative by North Queensland Bulk Ports (NQBP) where the port has undertaken bathymetric and topographic laser scanning of their rock armoured breakwaters and revetments since the early 2013. This now occurs before cyclone season and after every major event and maintenance, repair or upgrade campaign undertaken across their assets. The surveys are undertaken by the Port of Brisbane and include a combined multibeam and laser survey. By undertaking these surveying works at regular intervals, NQBP ensures it has a consistent basis for the monitoring of their assets and the port is accurately able to ascertain mechanisms for failure and areas of susceptibility during specific events.

Effective Use of 3D Data for damage assessment – Surface Analysis Heat Maps

While high resolution point clouds can be data intensive and seemingly unwieldy, if captured on a regular and consistent basis they can be post-processed with relatively ease to form more manageable 3D surfaces that can be compared throughout the life of an asset.

To assess damage extent and design repairs to remediate the damage inflicted upon NQBP's assets during Tropical Cyclone (TC) Debbie in March 2017, 3D surfaces from the existing point clouds were generated and compared for two specific functions. Firstly, surface comparisons were undertaken between the pre- and post-storm point cloud data, and secondly the post storm surface was compared with the ultimate repair design profiles. This second comparison function is discussed further in Section 5.

The pre- and post-event surface comparison maps (heat maps) as seen in Figure 1 were developed at the start of the project as a tool to assess the extent of damage to the assets. These heat maps assisted in defining the:

- magnitude of damage relative to values for volume loss/ gain and for surface area with elevation loss/ gain;
- likely mechanisms of failure;
- areas susceptible to damage, (particularly under TC Debbie conditions);
- trends in armour displacement and/or accretion along the structures; and
- definition of specific segments of the assets based on performance and extent of damages.

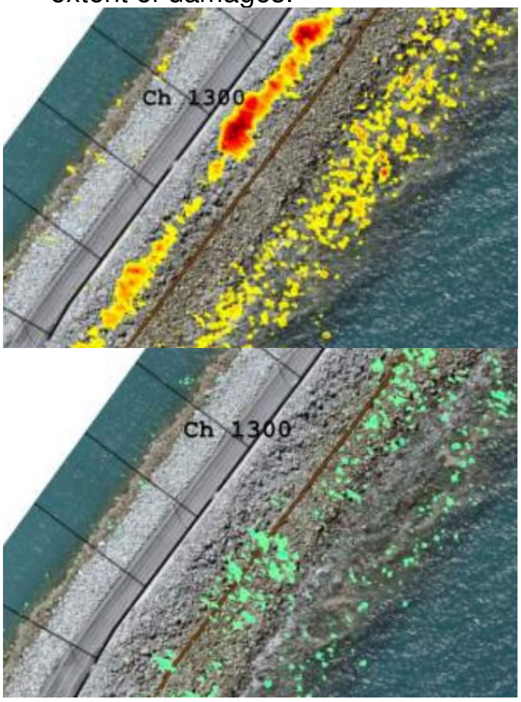

Figure 1 – Plan view excerpt from heat map of damaged breakwater showing example surface comparison maps with the top image showing elevation loss scaling from yellow (minor) through to red (major) and the bottom image showing elevation gain scaling from green (minor) through to blue (major)

Further to this, the heat maps informed the site inspections allowing areas of damage to be identified easily on site where it is sometimes difficult to determine from vision alone. Site investigations were therefore able to clarify the extent of damage relative to the heat maps. The heat maps were then assessed against structural ratings in accordance with both the Rock Manual (CIRIA, 2007) and Coastal Engineering Manual (USACE, 2002). The Rock Manual provides recommendation on typical associated maintenance relative to the assessment against structural ratings. These recommendations can guide decision making on suggested actions including repair or rehabilitation.

For example, where armour rock was displaced such that core or underlayer were lost, this would constitute major damage and in accordance with the structural ratings and typical associated maintenance would include rehabilitation of the asset.

Damage Criteria and Scoping Repairs

The heat maps provide a concise method for understanding extent of damage to rock armoured assets. However, to efficiently define the scope of repairs an appropriate definition of damages and criteria for remedial works is required.

For the purposes of the TC Debbie repairs, the scope of works required the assets to be returned to a level of service equal to that seen prior to the event as a minimum. The scope was limited to this extent due to the nature of the insurance policy. For this reason, where there was erosion or dislodgement of armour units it was expected that these areas would be remediated.

The heat maps were refined to remove negligible (or no) damage as defined by the descriptive rating guidance for armour loss (CIRIA, 2007). This removed surface elevation differences less than ¼ of the diameter of one primary armour rock (0.25 * D_{50}). The sensitivity of this value was tested (Figure 2) with surface elevation loss between ¼, ½ and ¾ of the diameter of the mean primary armour being removed across separate maps.

The areas of damage identified across these subsequent heat maps remained relatively consistent in identifying areas requiring repair.

Figure 2 - Example of a 'heat map' showing breakwater damaged area (yellow = elevation loss). On the right surface elevation loss of greater than 0.2m diameter is shown. Comparing this to the map on the left shows the sensitivity in adopting a surface elevation loss of greater than 0.5m (i.e. approx. 40% of diameter)

Surface Analysis Maps – Limitations

There are a number of limitations to using the surface analysis heat maps. Some of these are noted below.

Heat maps require consideration of coastal structures that may be considered at design to be dynamic (for example reshaping berms). This limitation can be mitigated through appropriate definition of damages and a threshold for repairs in the damage criteria and scope and by assessing the elevation loss heat maps against the elevation gain heat maps to determine trends in armour movement including loss, accretion and dynamic equilibrium.

The volume outputs of the surface analysis provide an indication of the volume of lost armour but not necessarily the volume required for reinstatement of the asset. This was observed to be largely due to two mechanisms:

- Small or broken armour needed to be removed from the profile prior to repairs.
- The armour required to reinstate the asset needed to be larger in diameter than the void left by the displaced armour. This was seen to be due to:
    - dislodged armour was smaller than the mean design armour;
    - voids left by dislodged armour led to slumping of armour above, partially filling the void;
    - voids left by dislodged armour were partially filled with mobile smaller armour from adjacent sections of the breakwater (e.g. from dynamic berm below upper profile).

Effective Use of 3D Data to quantify repair design – Repair Surface Model

To assist in quantifying the rock armour quantities required for repairs, a 3D model of the design surface can be prepared. Quantifying the volume of rock armour will require consideration of the type of repairs being undertaken and if the additional armour will be incorporated into existing armour layers or whether the existing layers will be reprofiled and prepared for overlaying of subsequent armour.

The TC Debbie repairs were designed to minimise repair quantities and were based on repair strategies aligned with those defined in the Rock Manual. These varied from spot or localised repairs to a complete overlay and rebuild of two layers of primary armour. Quantifying the armour required for these different repair strategies required consideration of:

- The quantity of existing armour to be incorporated into the repaired primary armour profile; and

- The quantity of the existing armour within the repaired profile that met the specification for the rock armour for the repairs.

Where the existing armour within the repair profile did not meet the specification, it was expected that this would be removed from the profile and placed at the toe of the structure.

For all repair strategies where existing amour was to be incorporated into the repair profile, the following procedure was used to quantify the repairs (refer Figure 3, which provides a cross section of the volume analysis).

- The design surface was compared to the post-storm survey surface providing an initial volume estimate (V_1).
- The volume for the whole repair profile was calculated (V_2).
- The volume of the existing armour within the repair profile (V_3) was calculated (V_2 minus V_1).
- The volume of the existing armour that met the specification of the repairs (V_4) was estimated by applying a percentage of retention (R) based on inspection of the existing profile (V_3*R).
- The final estimated volume for each segment of the breakwater was calculated by subtracting V_4 from V_2.

While V_1 would logically provide an appropriate quantity estimate, if the existing armour within the design profile (V_3) is not of appropriate size or quality, this armour would be removed from the repaired profile. For the TC Debbie repairs, this value fluctuated based on site observations, but due to the wide grade and range of rock characteristics seen across the structures, the percentage of retention was typically approximately 40%.

For the TC Debbie repairs the volume of existing armour (V_3) and the retention parameter had a significant impact on the estimated quantities. To minimise the rock armour required for the repairs, the existing rock profile was generally designed to be well within the cross section of the repair. This targeted a significant reuse of the existing material (maximise V_3) and minimised the potential for encroachment of the structural footprint.

Due to the scale of the works and the impact of the rock armour quantities on the tendering processes, the quantity output from the repair surface model was cross checked through an empirical approach. For every 25m section of the assets this involved:

- Calculating the surface area where there had been a change in elevation of more than 0.5m (or approximately 40% of the diameter of the mean armour rock).
- Applying this plan view surface area along the relevant sloped profile to gain an actual damaged surface area.
- Multiplying the actual surface area by the diameter of the design mean armour rock (or, where two armour layers were proposed for the repairs, the surface area was multiplied by twice the nominal diameter of the mean rock size).

This initial quantity estimate was then reduced by estimating the volume of accreted armour, or where the surface elevation had increased by more than 0.5m. The same process was used to estimate accreted armour units in each 25m section, however it was expected that only a certain percentage of accreted armour could be recovered and incorporated in the repairs. A retention percentage was therefore applied which was on average 20%, but was assessed on the heat maps for each 25m section based on assessment of whether the armour was considered lost. Lost armour was defined to be either where it had been:

- taken over the crest of the breakwater by wave overtopping;
- shifted outside the reach of a typical long reach excavator;

- located below Mean Low Water Neaps; or,
- based on inspection, if it was damaged such that it no longer met the armour specification.

The empirical check on the quantities generated from the repair surface model provided results that holistically deviated no more than 10% across three of the four structures. The fourth structure had considerable limitations with the coverage of the existing survey data. This process provided confidence that the volumes generated from the repair surface model were appropriate for tendering.

Implementation and impact of effective data capture in breakwater repair

There are many advantages in the use of 3D data for damage assessments and repairs of rock armoured assets that largely stem from the ability to quantify and visually present findings from a reliable and less subjective basis than conventional methods.

As noted in the introduction, the collection of 3D data can provide an exceptional basis upon which to develop a business case for repair and/or upgrade of coastal assets. Heat maps not only provide volumetric outputs to quantify changes to assets, but also provide a simple tool for visual assessment and presentation.

While visual inspection of NQBP's assets after TC Debbie did identify areas of significant damage, the scale of the damages sustained, particularly below crest level, were not immediately appreciated prior to comparison of pre- and post-storm survey surfaces. The presentation of the heat maps and their volumetric outputs streamlined the approvals from relevant authorities and allowed for accurate preliminary budgeting.

After undertaking the thorough analysis of repair quantities, a number of risks were identified based on assumptions made during the design process.

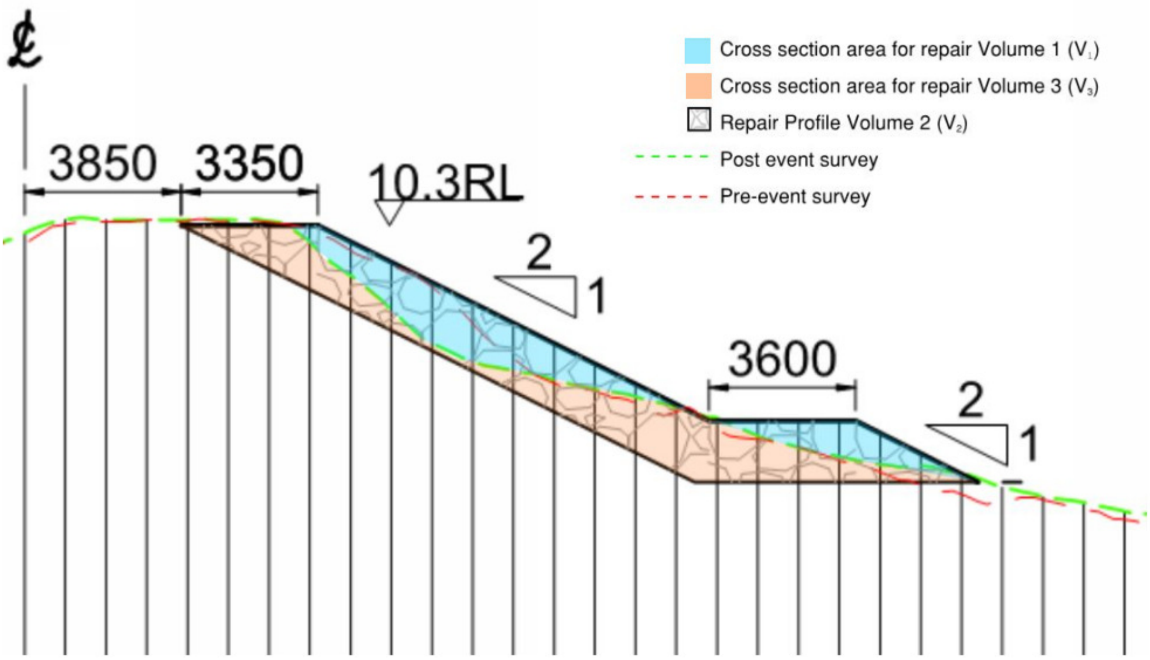

Figure 3 - Cross section excerpt of proposed repair profile with shaded areas for V_1 (blue) and V_3 (orange) as well as the pre- and post-event survey

Assigning quantities to these risks based on existing research or conservative consideration allowed both a targeted rock armour quantity and an upper limit quantity that incorporated these risks to be defined. This allowed budgets to be planned and refined. Risk quantities for projecting upper limits included:

- Assumed percentage of voids;
- Assumed unit weight of the rock armour;
- Overestimation of retention percentage (R);
- Loss of armour at toe due to seabed material uncertainties;
- Uncertainties in the profile and the extents of the assets where there were gaps in the existing survey data.

This process was specifically important for the TC Debbie repairs as, to manage risks associated with rock armour supply and minimise inclusion of contingency in contractor pricing, the contracts were procured on a schedule of rates basis. Upon confirming the preferred Contractors, pre-tender estimates on rock supply and placement rates could be used to set targeted and upper limit contract budgets.

During the construction phase the targeted quantity estimates were used to track progress, provide continual revision of budgets and monitor the grading of placed rock armour. Quantities placed were tracked for every 25m (refer Figure 4) and allowed for controls to be placed on the Contractor by assigning hold and witness points for growth in placed volumes against targeted volumes. This led to an effective approach to monitoring the progress of the repairs and tracking contractor progress against budgets and the risks incorporated into the upper limit quantities. For this example, actual rock placed aligned well with pre-tender estimates (targeted quantities), which gave confidence in the approach taken and allowed the project to be delivered within budget

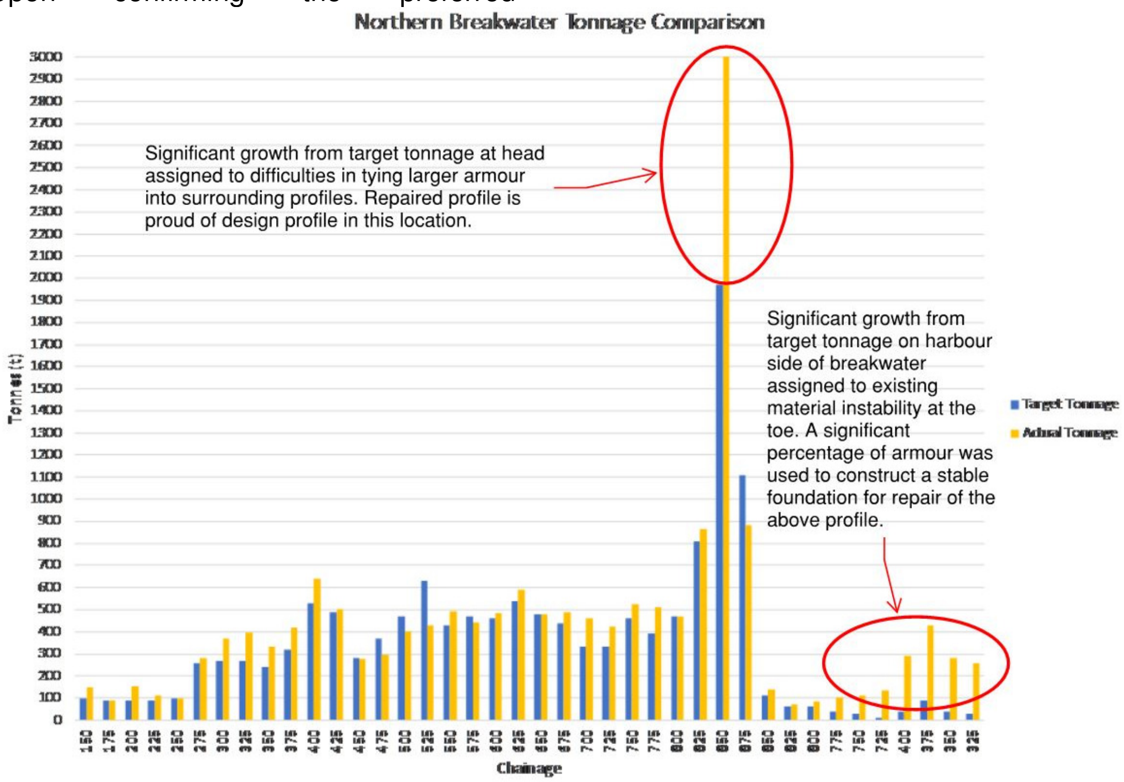

Figure 4 - Tracking spreadsheet for the Northern Breakwater repairs at the Port of Mackay showing target tonnages per 25m section (blue) against placed tonnages (yellow). Note the good correlation as well as outliers that were assigned to relevant risks determined during the design phase

Conclusions

Regular and consistent data capture and a clearly defined damage criterion can enable an effective approach to the management and repairs of rock armoured assets. Surface comparison and similar models that can be readily generated from point cloud data provide the basis for transparent business cases for repairs and upgrades. This can provide justification through a consistent format for substantiating and quantifying damage, which is advantageous as:

- it allows for concise presentation of requirements to gain approvals from key stakeholders and/or authorities
- it can improve quantifying, budgeting, planning, procuring and managing construction.

Relevant to the TC Debbie repairs undertaken at the Port of Mackay the volumetric analysis using existing point cloud data and 3D repair design profiles facilitated effective project delivery that is on target to be delivered within allocated budgets and project programme window. The 3D point cloud data captured by NQBP allowed the development of a concise business case for project approvals, effective quantification of repair armour requirements and an effective means of tracking project progress and revising associated budgets and programmes.

The significant benefits demonstrated by the Port of Mackay breakwater TC Debbie repairs example suggests that coastal asset owners should consider incorporating regular 3D detailed data capture of their critical assets to best inform a post-storm damage recovery strategy should this eventuate.

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