Pumped Beach Replenishment in Adelaide: Selecting the Design Sand

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Abstract
Variations in the grain sizes of beach sand along the Adelaide metropolitan coast have been investigated in relation to assessing likely pumping efficiency and practicality for a proposed change in beach replenishment methods from sand carting to sand pumping. Pumping rates, achievable slurry concentrations and pump and pipeline design parameters are examined for the range of sands occurring in the mid-coast sand accumulation areas of the Adelaide coast. Determination of the 'design sand' is a critical aspect of the sand pumping infrastructure proposed, as it influences pipe wear and pump size with pumps that could be operating at peak capacity, possibly requiring two pumps per station. The paper includes results from recent and historic sand sampling and analysis work. The influence of nearly 40 years of beach replenishment and concurrent sediment transport processes on sand characteristics and distribution is discussed with some projections made of likely future sand characteristics. The November 2010 sand pumping trials are outlined, with results presented for dredged pumping of 'fine' and 'coarse' sands at a range of slurry concentrations in a 285 mm ID test pipe of 400 m length.

Keywords: beach replenishment, beach nourishment, slurry pumping, sediment grain size

1. Introduction

The paper outlines the history to the selection of a 'design sand' in the development of a new sand slurry pumping system for beach replenishment of Adelaide's beaches, and discusses the investigations and experiments conducted to determine the design sand for the system and the influence of the design sand on the design and its sensitivity to variations in sand characteristics.

2. Background

Adelaide's urban coastline of approximately 28 km has been replenished for nearly 40 years to counter recession of its southern to mid-coast sections. Initial replenishment rates were low, with trucks carting sand from accumulation areas, southward to eroding areas, ie 'backpassing' sand within the greater littoral cell. In the 1980s carting within the littoral cell was augmented with sand dredged from offshore sources and small quantities from onshore quarries. In the late 1990s two small harbours built within the littoral cell, required sand to be bypassed to maintain littoral drift along the coast, continuing a whole of littoral cell backpassing approach to managing the coast.

In 2005, with the adoption of the State Government's Adelaide's Living Beaches (ALB) strategy [1], the metropolitan coastline was philosophically segmented into seven sand management cells. These cells were set by the littoral boundaries of the new harbours and other features that influenced littoral drift. The new strategy retained beach replenishment as the means of coastal protection and management but aimed to integrate sand management at the harbours into beach management by recycling (backpassing) sand within each sand management cell rather than along the greater littoral cell as a whole. The advantage of this approach is that expense and energy to collect and handle sand would be directed to backpassing of sand from where it accumulates and keeping it further south in the system. The Adelaide beaches are characterised by limited deposits of sand suitable for beach replenishment and the loss of beach compatible sand to the northern beaches where large quantities of finer sand also accumulate. The recycling approach will conserve beach compatible sand and reduce the costs of maintenance dredging of the harbours.

The approach of the ALB strategy is that sand recycled within the littoral cells would be collected by beach-based sand collection units and dredges and transported by slurry pumping to fixed discharge points, which had been selected to include past, current and future erosion hotspots.

The sand pumping scheme and its operation is to be provided under a 20 year Design Construct Operate and Maintain (DCOM) contract. The Sand Transfer Infrastructure (STI) project was originally to pump sand within four of the sand management cells, with the ability to pump sand southward between cells. Its entire length was to be 22 km, with four main pump stations, seven booster pump stations separated by approximately 2 km, but up to 2.8 km intervals. The locations of main and booster pump stations were restricted by the densely urban nature of the foreshore, with existing parks being favoured to limit visual impacts to residents and businesses. The system would have the capacity to pump 75,000 m^3 of sand in each cell per annum, within operating hours restricted to day working hours from 7am to

7pm and with constraints on days of work, including public holidays and hot weather.

Normal slurry pumping concentrations sought during operation were 35% by weight. Sand to be pumped was described as an average median diameter (d_{50}) of 0.22 mm but sand of a 'maximum d_{50} grain size of 0.5 mm' also needed to be pumped. The system needed to be able to operate within the local environment, including frequent, although unpredictable high levels of seagrass wrack, local wave and tide climate and the necessity to meet bathing water quality standards in the marine water nearby slurry discharge points.

3. Concept Design for the project

Initial scoping for the project included a Registration of Interest (RoI) for technical advice on sand pumping, in 2006. Assisted in-house concept development was followed by the appointment of professional services consultants (project management, technical services and cost managers), in 2008, for preparation of a Concept Design. Following a call, in late 2008, for Expressions of Interest (EoI) from the market in undertaking an anticipated DCOM contract; short-listed consortia were invited to tender for the DCOM contract in September 2009, with tenders closing in December 2009.

During tender assessment and negotiation it was identified that aspects of the Principal's Project Requirements (PPR) required critical review and that the tenderers could not achieve the full project within the budget available. The independent consultant, Dr Allan Thomas was appointed to assist with review of slurry pumping and hydraulics design aspects of the tender assessment.

The STI project was adjusted in September 2010 to include slurry pipelines in only the two cells that had the greatest benefits in cost effectiveness of slurry pumping over sand carting, and greatest recreational benefits through reduced disruption to use of the beaches. The shorter scheme has a combined pipeline length of 9 km, two main pump stations and three booster pump stations. Sand characteristics and slurry densities required to be pumped were adjusted including additional information about grain size distribution from a November 2009 sample program. A revised PPR was released in October 2010 to the preferred tenderer inviting a revised tender. A revised tender was received in February 2011, with tender negotiation continuing during writing of this paper.

Development of the concept design focussed on the necessity to manage dead seagrass material entrained within and accumulated on and within the sand deposits. Evaluation of the initial tenders and preliminary design information identified the critical nature of sand grain distribution as well as d_{50} grain size in the hydraulic design for the STI. Results of some sand samples, notably at low water mark (LWM) at one of the source beaches for sand collection, showed some much larger grain size sand than is generally expected on Adelaide's beaches. Dr Allan Thomas was engaged to assist in the tender evaluation for the STI and also to understand the influence of grain size distribution on pumping system design and operation and to identify how this matter could be better represented to improve certainty for both principal and tenderer.

4. Characteristics of Adelaide's beach sand

4.1 Historic sand observations

Sand characteristics for Adelaide beaches were documented in 1970 from samples taken in 1966. The sand is over 90% silica sand on all but the northernmost beaches. The d_{50} of the majority of samples was between 0.2 and 0.3 mm for locations at LWM, HWM and above HWM, along the coast. The highest d_{50} was 0.5 mm at mid-coast and southern locations, with d_{50}s between 0.17 and 0.2 mm on the northern accreting beaches. These are detailed in the Department of Environment and Natural Resources Technical Report 2010/2, [2].

Since that time, beach replenishment including the 'backpassing' of over 1 million cubic metres of sand and a further approximately 1 million cubic metres of dredged sand from the offshore Port Stanvac source as well as small quantities from other sources have been added to the southern beaches. The Port Stanvac sand had distinctly bimodal characteristics, with about 20% of grains being between 0.425 and 1.18 mm sieves and over 40% of grains finer than 0.212 mm sieve. When hydraulically placed on the beach it was observed that waves quickly sorted the finer sand seaward and further along the beach, transporting it along the sand bar. The results of limited post-replenishment beach sampling reflect this observation, as shown in Figure 1, where the 1982 sample of beach sand at Brighton is used as a benchmark.

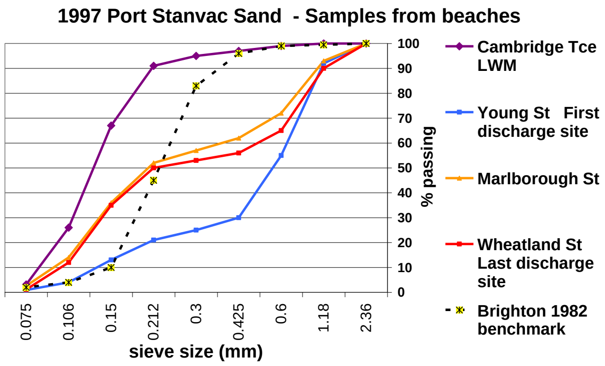

Figure 1: Note the finer grading of the sand at the low water mark (LWM) at the more northerly Cambridge Tce location, compared with the 1982 benchmark sand from Brighton and the coarser grading of the wave-washed sand from the first placed Young Street location (in blue).

4.2 Present sand

A sand sampling program in 2002 was part of investigations for the ALB strategy; samples obtained at LWM and HWM indicated similar d_{50}s to the 1966 sample results, with the exception of two samples toward the southern beaches, with d_{50}s of 0.7 mm and 0.58 mm at HWM and LWM. The standard sample sieving includes shell; then samples are acid washed, % weight reduction is noted – usually of the order of 5% to 10%, though this data is not further referred to in this paper.

Further sampling in November 2009 was more intensive but focussed on the sand accumulation areas for the STI project. Samples in the southernmost sand management cell were the coarsest with some particularly coarse sand at LWM as shown in Figure 2.

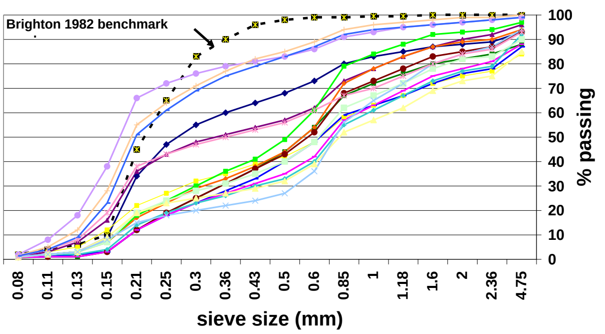

Figure 2: Samples from LWM at the sand accumulation beach; note that many of the samples have d_{50}s greater than 0.5mm and a significant portion of sand with grain size greater than 1mm.

In light of the unexpectedly coarse sand at the planned STI source site for the main southern sand management cell, and an increased understanding of the significance of the coarse sand in hydraulic design of the STI, additional sampling along the beaches was undertaken in 2010. The sampling program aimed to 'look into the future' by sampling sand that will drift into the accumulation area and to investigate whether the very high d_{50} sands sampled in 2009 were representative of the sand that was likely to accumulate in the future. Figure 3 shows the range of sands found within the southern sand management cell sampled at MWM and HWM in November 2010, compared with the benchmark 1982 sample.

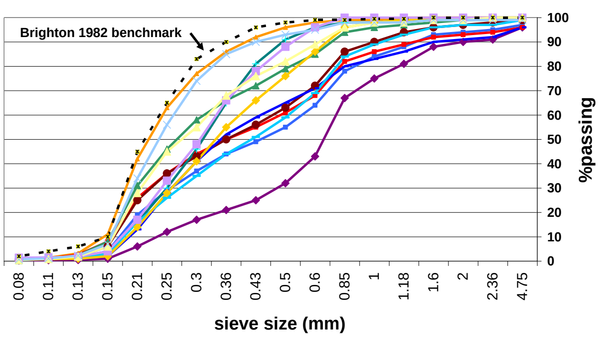

Figure 3: Sand samples throughout the southern sand management cell – note that they are generally less coarse than the 2009 samples in Figure 2.

Tide conditions at the time of sampling limited the seaward extent of samples obtained and LWM samples could not be obtained.

Further samples at the source sites for the STI project were taken and analysed in less detail with a wet-sieving method but with a focus on the proportions of the sample passing 1 mm and 0.5 mm sieves as this range was considered to be useful in indicating the suitability of the sand for slurry pumping efficiently. It was found that on average, 74% of the sand would pass the 0.5 mm sieve. It is noted that checking of the method for four samples using conventional analysis indicates that the wet sieve test method underestimates these proportions by approximately 8%.

4.3 Characteristics of sand in the future

With a design period of 25 years, any changes in the distribution of grain size of accumulating sand over time could affect the system efficiency. As well as the characteristics of the sand already within the littoral system (both 'native' and fill sands) the factors influencing future sand characteristics are twofold; the characteristics of sand added to the system through future replenishment of beaches from outside sources, and relative differences in sand movement for different grain sizes due to littoral drift or other physical processes. The latter would include sorting of sand if it is collected by the STI selectively on grain size, or different relative rates of littoral drift of the beach sands.

It is conjectured that sand moving from the southernmost sand management cells to beaches to the north has been filtered by the built obstructions of harbours, possibly contributed to by the practice of sand bypassing at the harbours (predominantly by dredge) since the late 1990s. This could have increased the d_{50} in the southern onshore accumulation areas resulting in the recent observations of locally high d_{50}s. The change in replenishment methods with the STI concentrating on removing sand from the upper beach may reduce this sorting influence.

The ALB strategy includes an ongoing program of addition of sand from external sources to the southern beaches, as a measure against sea level rise and other sand losses. The sources identified to date for this sand are not as coarse as the sand dredged onshore from the Port Stanvac source in the previous major replenishment programs.

Figure 5 shows historic changes in d_{50} along the coast.

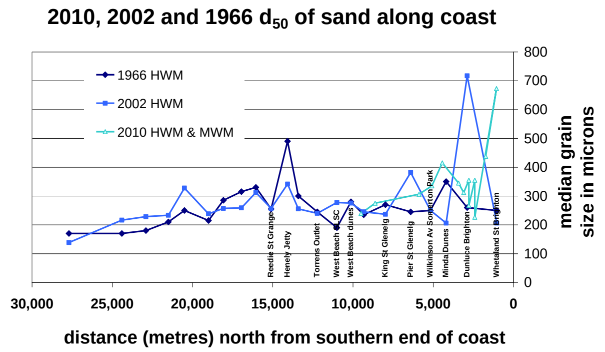

Figure 5: Changes in d_{50} over time; spikes in sand coarseness on the right hand side (the southern end of the coast) are considered to reflect the large dredged replenishment campaigns of the 1990s and are expected to move northward (left) and reduce over time.

Considering the potential variety of sources and characteristics of future replenishment sand, including scope for pre-treatment of sand (such as washing to remove fines) emphasises the desirability that the STI be able to pump a broad range of sands. The large volume of sand already on the beach and effectiveness of the STI in 'recycling' the range of grain sizes accumulated are viewed as influences that narrow the range to be specified for handling by the STI. Monitoring grain size distribution will be part of the ALB strategy.

5. Influence of sand characteristics on hydraulics and pipeline design

Key to the efficiency of the STI project is the concentration of sand able to be pumped as slurry and hence the sizing of pumps, motors and electricity supply infrastructure to achieve its operation. The defining feature for system sizing is the minimum flow rate needed to minimise bed load in the pipes and this is strongly dependent on grain size of the material pumped. Furthermore the range of sand sizes (both in time and within the source deposit) is of critical interest.

5.1 Deposit velocity, slurry concentration and head loss gradient

Methods to estimate deposit velocity for narrow-size distribution sands in various diameter pipes are available such as Wilson and Judge, 1978 [7]. That the sand at Adelaide has been shown to have an occasionally broad size distribution means that simple use of d_{50} to represent the material is not suitable, as large proportions of the sand can be much coarser, with higher deposit velocities. To conservatively estimate the effect of the coarser fraction, an analysis of the system was undertaken using d_m, the 'weighted mean diameter' in place of d_{50}, as documented in Govier and Aziz (1972) [4] amongst others. The d_m is calculated as per Equation 1:

$$d_m = \Sigma\, d_i\, m_i \qquad (1)$$

Where d_i is the median size between two consecutive sieve sizes and m_i is the mass fraction between those two sieve sizes.

The d_m for the November 2009 samples have been calculated and give significantly higher values than the d_{50}. For example the highest d_{50} for the sample set was 0.8 mm and the corresponding d_m is 1.98 mm. The average d_m of all samples in the southern sand management cell is 0.64 mm, compared with an average d_{50} over the same samples of 0.29 mm.

The concentration also influences the deposit velocity. The deposit velocity for sand in a 226 mm ID pipe has been estimated as 3.25 m/s for slurry concentrations above 25% by weight and d_{50} of 0.5 mm. However, if the slurry concentration is reduced to 15%, then the deposit velocity for the material is predicted to reduce to 2.3 m/s. The lower deposit velocity would allow the pumping velocity to be reduced at the lower concentration with consequent reduction in head loss gradient, but would require a longer pumping time to obtain the same solids throughput.

Methods of predicting the head loss gradient for sand-water slurries are described in Wilson et al 2009 [6]. Thomas 1977 [5] discusses the different behaviour of fine and coarse sand and the effects on head loss gradient.

5.4 Pipe wear and roughness

Pipe wear rates vary at between the square and cube of the velocity, so increasing flow velocity in the design to pump the coarse fraction of sand will have a considerable influence on wear rates. Apart from the velocity effect, the coarser particles also increase pipe wear at least in direct proportion to the particle size. These general models are based on the discussion of impact and sliding wear for bed load slurries in Section 11.4 and Figure 11.6 of Wilson et al, 2009 [6].

The hydraulic roughness of the pipe influences the slurry head loss gradient. For example in the dredge slurry pumping trials discussed later in Section 6, the roughness of the used HDPE dredge pipe was found to be around 0.15 mm. This compares with a roughness of around 0.01 mm for new HDPE pipe. For water flowing at 4 m/s in the 285 mm ID pipe the Reynolds Number is 1.1×10^6 and a standard friction factor chart indicates a 43% increase in the water head loss gradient as the roughness is increased from 0.01 mm to 0.15 mm. For slurry, the increase is less because there is a solid friction component. For example for a fine sand (d_{50} = 0.26 mm) slurry at 4 m/s, the increase in head loss gradient is predicted to be 35% when the roughness increases from 0.01 mm to 0.15 mm. For a coarse sand (d_{50} = 0.43 mm) the increase is 24%.

6. Slurry Pumping Trials

6.1 Intent of trials

The prototype scale slurry pumping trials held on the 10th and 11th of November 2010 were instigated to provide head loss gradient information for pumping the fine and coarse sands that occur on Adelaide beaches at a range of slurry concentrations. These full-scale tests aimed to demonstrate the slurry concentrations that could be reliably pumped for the coarser material and the corresponding head loss gradients.

6.2 Description of the trials

A stockpile of 3,000m^3 of selected 'coarse' sand was collected by land plane and carted by truck to the trial location, mixed by dozer, and formed into a pile within the harbour from which the cutter suction dredge could work the seaward face. In an adjacent part of the harbour, there was also a deposit of finer sand (accumulation within the harbour) which the dredge could readily be repositioned to work on. The pipeline assembled for the trial was a well-worn 500 metre long 315 OD HDPE PN8 pipe (ID 285 mm) laid near horizontal along the beach fitted with upstream and downstream pressure gauges and differential pressure (DP) sensors across a 16 m test section, 168 m from the dredge. Flow rate was measured by the dredge's ultrasonic flow meter and by a doppler meter installed adjacent the upstream DP sensor. The dredge's nuclear density meter was used for slurry concentration.

A range of tests were run, including water pumping tests (from 500 to 1,800 m^3/hr flow), coarse sand slurry tests (at 5%,15%, 25%, 35% and up to 55% slurry by weight and flow rates of up to 980 m^3/hr), and fine sand tests (at 25% and 30% slurry concentration by weight). Test conditions were maintained at steady flow and concentration for as long as possible (a few minutes) to endeavour to achieve steady state conditions within the pipe length. At 4 m/s the transit time is 2 minutes.

Source and discharge sands for the tests were sampled for particle size analysis. Pipeline lengths and elevations were surveyed and recorded. General observations such as flow steadiness, discharge material consistency, presence of rocks or shelly loads and periods of high turbidity of discharge were noted.

Details are recorded in Department of Environment and Natural Resources Technical Report 2010/1, DENR (2010) [3].

6.3 Results from trials

Figure 6 compares the dredge trial's coarse and fine sand particle sizings. The respective d_{50} sizes are 0.42 mm and 0.26 mm with the respective d_m sizes 1.42 mm and 0.40 mm.

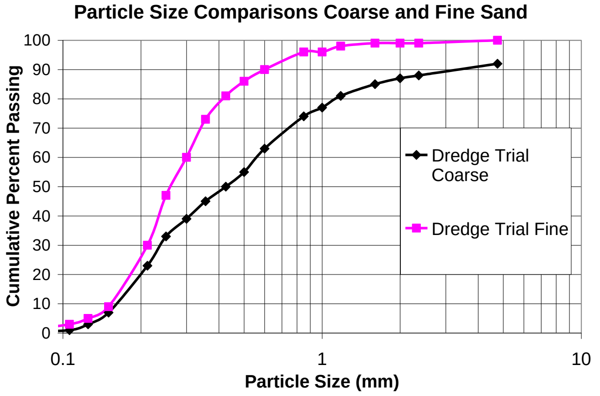

Figure 6: Particle size of coarse and fine sand pumped in dredge slurry pumping trials.

The slurry pumping trials demonstrated that, at a velocity of 3.5 m/s, the pumping of the fine sand was hydraulically similar to pumping clear water; ie the head loss gradient in metres of slurry per metre was similar. However, pumping the coarse sand required the velocity to be increased to around 4.5 m/s to achieve a similar head loss gradient as water and the corresponding head loss to achieve the required velocity was around double that of the fine sand at 3.5 m/s. This is shown in Figure 7. The upper curve is the predicted head loss gradient for the coarse sand, the curve below the prediction for the fine sand and the dashed curve the water head loss gradient.

The predicted deposit velocities are 3.2 m/s for the fine sand and 3.9 m/s for the coarse sand. The coarse sand test data below 3.9 m/s are therefore predicted to involve a stationary bed of particles. The flattening of the coarse data trend and the increased scatter below 3.9 m/s, are consistent with the presence of a stationary bed.

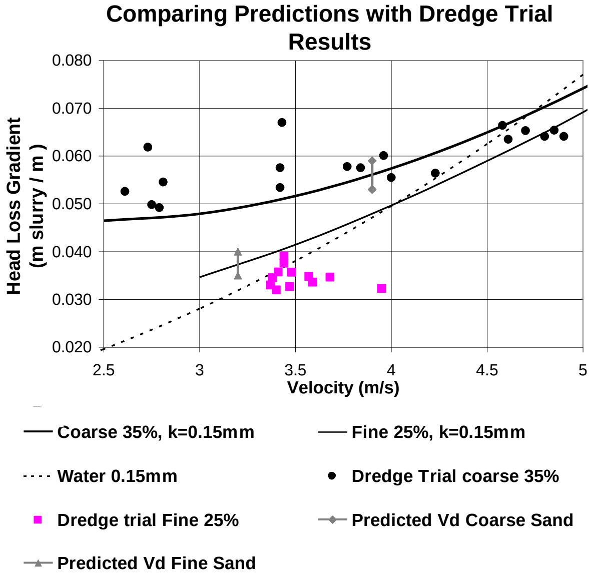

Figure 7: Head loss and deposit velocity predictions and data from the slurry pumping trials. Predictions are based on a pipe roughness of 0.15 mm reflecting the heavily worn pipe used in the trial.

7. Discussion

The sand present on Adelaide beaches exhibits large variations both in d_{50} size and size distribution. Considerable variations occur both longitudinally (along the coast) and transversely (across the beach). The range of sands reflects current and historical influences both natural and man-made. The future sand movement patterns and addition of sand from outside the system will also change sand sizes over the project life.

The selection of the design sand for the ALB STI project needed to reflect the most frequently encountered and more extreme sand characteristic ranges over which the pipeline would need to operate - with the focus on its ability to function in the extreme situations and operate efficiently under most conditions. On the other hand, specifying too broad of range of sand sizes to be handled could result in a design oversized for normal operation and hence less efficient for most of its operation as well as having a higher capital cost.

The ability to collect sand across a wide area of the accumulation beach and so mix coarse sand deposits with finer material is seen as an essential means of managing the characteristics of sand to be pumped. Trials on suitable equipment to collect sand from the beach have shown that using a sand scraper device is effective in providing sand to the pumping system with mixed characteristics from across the available beach width.

The most significant influence on the future sand characteristics of the Adelaide beach system will be the type of sand that is introduced to compensate for the impact of climate change. It is expected that over the 25 year life of the sand pumping infrastructure that sea level will rise by around 150 mm or more, with an anticipated increase in storm intensity, amongst other climate changes. Modelling of drift rates under these conditions indicates increases and the occurrence of erosion hotspots – but that the location of these is not consistent between the various scenarios modelled. The ALB strategy includes the addition of coarse sand from outside sources on an ongoing basis to manage these changes. The offshore movement of sand during storms is very dependent on sand size. Models indicate that, given the same storm conditions, the volume of sand eroded from a beach of d_{50} 0.5 mm sand is only 20% of that removed from a beach of d_{50} 0.22 mm sand.

Specifying imported sand will need to take account of a number of factors including:

- The economics of pumping the sand.
- Resulting beach slope and consequent longshore and offshore sand transport.
- Cost of meeting the required specification.
- Use of less costly, existing finer sand from northern Adelaide beach accumulation.

8. Conclusion

The design sand chosen for the revised PPR for the STI was described as follows:

> '*For the purposes of this document and system performance under the Contract, the following sand characteristics are to be used:*
> - *average d_{50} grain size varies between 0.22 mm and 0.50 mm, taking into consideration that this is variable within and between collection sites, and that the sand transfer operation may need to handle up to an average d_{50} grain size of 0.50 mm for extended periods;*
> - *maximum d_{50} grain size of 1.00 mm.*'

Recommendations for managing the impact of the varying sand characteristics occurring on Adelaide beaches on the STI include:

- Collecting sand in a cross-shore manner, so that extremes of coarse sand are avoided.
- Monitoring pipe wear, using a removable pipe insert.
- Varying flows to vary the location of pipe wear within the pipe (ie distribute wear more evenly between base and lower sides of the pipe).
- Increase the wear allowance for high pressure sections of pipeline to reduce risk of pipe failure.
- Reduce flows when pumping finer sands.
- Considering the influence of imported sand characteristics on the existing beach sands, and its effect on the economics of pumping the sand.

9. References

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