8

ASPECTS OF MARINE PHYSICAL ENVIRONMENT

LYTTELTON PORT COMPANY

DEEPENING AND EXTENSION OF THE NAVIGATION CHANNEL

CHANNEL DEEPENING REPORT

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1.0 INTRODUCTION

1. The Lyttelton Port Company Limited (LPC) is seeking a resource consent to cover the extension and deepening of the Lyttelton Harbour navigation channel, to accommodate larger and deeper draft container vessels – a representative photograph of which is shown in Photograph No 1.

Photograph No 1

The channel will be deepened by approximately 4 m and extended by up to 5 km requiring the dredging of up to 18 million cubic metres of seabed material (the channel deepening project (CDP)). This volume also includes some construction related dredging associated with the rebuild of the port. It is intended that this material will be disposed of at a proposed new dredged material dump location outside the confines of the harbour, approximately 4 nautical miles beyond the Heads. Sediment dredged to maintain channel depth will also be dumped at a new offshore location subsequent to the completion of the capital dredging program.

2. The tidal currents and the nature of the seabed at the proposed dump site location have been investigated by OCEL Consultants NZ Limited (OCEL) as part of a study to determine where material dumped at the site, and not retained in the designated dump area, will be dispersed to. A trial dump of dredged material from the 'Pelican', the dredge used for contract maintenance dredging of the existing navigation channel was also carried out and the resulting turbidity plume tracked using an Acoustic Doppler Current Profiler (ADCP) instrument.

3. The investigation work on the coastal processes prevailing in Lyttelton Harbour and at the proposed dumping location has been undertaken in a number of distinct phases/campaigns over the last ten years starting with a tidal current survey using an ADCP in the mobile mode ,continuing with turbidity surveys using a nephelometer, investigation of the fluid mud layer using the NIMROD device and progressing to the offshore dump trial using the Pelican. The Sediment Trend Analysis (STA) technique was employed in 2012 to infer sediment transport pathways in the outer harbour.

4. In the last two years Metocean Solutions Limited (MSL) have undertaken numerical modelling of the turbidity plumes and sediment transport generated by the dumping of the dredged material. The modelling work, in particular sediment transport modelling for fine sediment, is leading edge, being a very recent development. While the earlier numerical modelling of the tidal currents and waves has been validated by measured data the same has yet to be established for the fine sediment transport or morphological

modelling. The morphological model while not yet validated provides insights into predicted transport pathways under combined current and wave forces. A plan has been developed to undertake a full validation of the morphological model in the near future. The practical work covered in this report records actual recorded data. The modelling work complements and extends the empirical investigation and data collection work covered by this report.

5. The dredged material will be fine grained, predominantly (60%) silt size material. This material can be readily mobilised by wave action, the principal determinant of sediment mobility both within and outside the confines of Lyttelton Harbour. The water particle velocities produced at the seabed by long period swell can mobilise the fine material into suspension and once suspended the material can be transported by tidal and turbidity currents, hence the interest in determining the speed and direction of those currents.

6. Tidal currents provide the principal transport mechanism for suspended sediment. These oscillate back and forward with the state of the tide often with a tidal residual or net movement in either the flow or ebb direction. Turbidity currents are significant for the initial dispersion of dredge hopper loads dumped onto the dump location but are a secondary transport mechanism thereafter because of the gentle subsea slopes. Turbid water accumulates in deeper water and depressions in the seabed such as the navigation channel because it is denser than seawater. The channel acts as a trap for turbid water and the entrained sediment settles out.

7. From experience, previous measurements and work specifically undertaken for this report it is known that there is a relatively high, natural, background level of turbidity both within Lyttelton Harbour and in Pegasus Bay outside the harbour. Measurements of turbidity in the harbour at various locations depths and times of the year have been undertaken by OCEL and correlated against existing Environment Canterbury turbidity data.

8. The turbidity measurements were made using OCEL's nephelometer which measures turbidity in NTU's (Nephelometric Turbidity Units) an expression of the optical properties of water that cause light to be scattered or absorbed and is directly related to turbidity. The actual quantity of sediment contained in collected water samples was measured to determine a TSS (Total Suspended Sediment) value and correlated with the NTU values.

9. It is the silt entrained in the water that gives the sea the characteristic aquamarine colour in harbour. While the seabed in Pegasus Bay is primarily sand there is a fluid silt layer on top of the sand. This layer is highly mobile and accumulates in seabed depressions – such as the trenches that were dredged for the Christchurch and Waimakariri ocean outfalls – as a dense fluid. In calm or short period seastate conditions this material is close to the seabed but becomes dispersed through the water column by turbulence associated with swell wave action.

10. This report builds on the large body of research work covered in earlier reports and studies by the LPC and its predecessor, the LHB, and by the geography department of the University of Canterbury under the supervision of Professor Kirk. It is less a ground breaking study than an extension to an existing knowledge base taking full advantage of the remarkable capabilities of the ADCP instrument to track and record tidal and turbidity currents enabling earlier conjecture to be replaced with fact. The extensive numerical modelling work undertaken by MSL to model currents, wave action and sediment, culminating in the development of a morphological model, is separately reported in MSL reports but referenced here because the earlier work and data collection covered in this report enables ground truthing of the MSL model projections.

11. Further work on tidal currents by Dr Derek Goring of Mulgor Consulting Limited (Mulgor), reported in Lyttelton Harbour: Hydrodynamics Update 2013, has utilised the ADCP in the static mode to track tidal currents at the deployment points and to determine residual currents. Mulgor has also undertaken computer modelling of tidal currents and verified the model results using the ADCP data. His work also established a correlation between turbidity and rainfall events. The Mulgor report complements and

extends the OCEL work and further increases the understanding of the Lyttelton Harbour hydrodynamic regime.

12. I consider myself privileged to have been involved in this work to develop a thorough understanding of the coastal environment and the Lyttelton Harbour regime over a 45 year period encompassing the evolution of current meters from ingenious clockwork powered devices through to sophisticated electronic devices with no moving parts based on Doppler frequency shifts. The developments in instrumentation in parallel with the exponential growth of computer power and the numerical modelling techniques that has made possible has enabled a close to complete understanding of the harbour and coastal environment. The LPC has also willingly employed new measurement and modelling techniques as they have emerged in the true spirit of unbiased scientific research to better understand the environment and avoid deleterious effects.

2.0 GEOMORPHOLOGY OF LYTTELTON HARBOUR AND PEGASUS BAY

2.1 Lyttelton Harbour

1. Lyttelton Harbour is the eroded caldera remnant of an extinct volcano, the older of two interlocking Miocene volcanoes that form Banks Peninsula – Lyttelton in the northwest and Akaroa in the southeast.. The high marine cliffs at the entrance to, and along the sides of, Lyttelton Harbour were cut during the Pleistocene age when the average sea levels were much lower. The cliffs were drowned when the sea level rose rapidly at the end of the last ice age.

2. The drowned cliffs and steeply sloping inside walls of the old crater plunge into the harbour and continue underwater until they intersect with a flat seabed. In its natural condition the seabed is unusually flat, both in harbour cross section and along the longitudinal axis of the harbour.

3. From the head of the harbour to the Heads is almost a constant 1:1000. The flatness is indicative of a fluid seabed condition. As a consequence of its naturally flat seabed and plunging sides waves running up the harbour in its unaltered state suffer little attenuation of wave energy through refraction.

4. Refraction effects generated by the channel however do reduce wave energy passing up the channel. That part of the wave front in the deeper water of the channel moves faster than the wave front lengths over the shallower water either side. The wave orthogonals, imaginary lines perpendicular to the wave front diverge out of the channel reflecting a dissipation of wave energy in the channel.

5. A natural equilibrium prevails that accounts for the flat seabed. Fine sediment disturbed by swell wave action becomes fluid, and is entrained as a suspension in the sea water. The material settles out in deeper areas as the swell wave energy subsides. Depressions such as the navigation channel are filled in and high spots are levelled. The shallower the water the higher the wave particle velocities – they decrease exponentially with depth – and the faster bottom sediment is disturbed and entrained. Disturbance of the seabed by swell waves, entrainment of sediment and subsequent settling out when the wave energy decreases is a constant of this environment.

6. The rock sides of the harbour mean that the seabed is the only boundary that is free to respond to coastal processes in the outer part of the harbour from Lyttelton to the Heads. The head of the harbour is characterised by mud flats exposed at low tide. The mud flats have developed principally from sediment runoff from the upper harbour catchment.

7. The fine sediments forming the seabed are predominantly (60%) silt size, primarily derived from the loess silt that mantles Banks Peninsula. The seabed sediment on the south side of the navigation channel however is slightly coarser than on the north side although this demarcation ends inside the Heads.

8. Fine sands are exposed on the seabed only on the south side. The harbour is further unusual in that the sediment size contours run parallel to the longitudinal axis of the harbour rather than normal to it.

2.2 Pegasus Bay

1. Pegasus Bay is a relatively shallow – both in plan form and depth - embayment north of, and in the lee of, Banks Peninsula. It is in the lee of Banks Peninsula with respect to the predominant wave and ocean current directions and is part of the continental shelf.

2. The continental shelf is relatively narrow off the end of the east tip of Banks Peninsula but extends directly north of the peninsula in the shape of a banner bank. See attached Figure No 1.

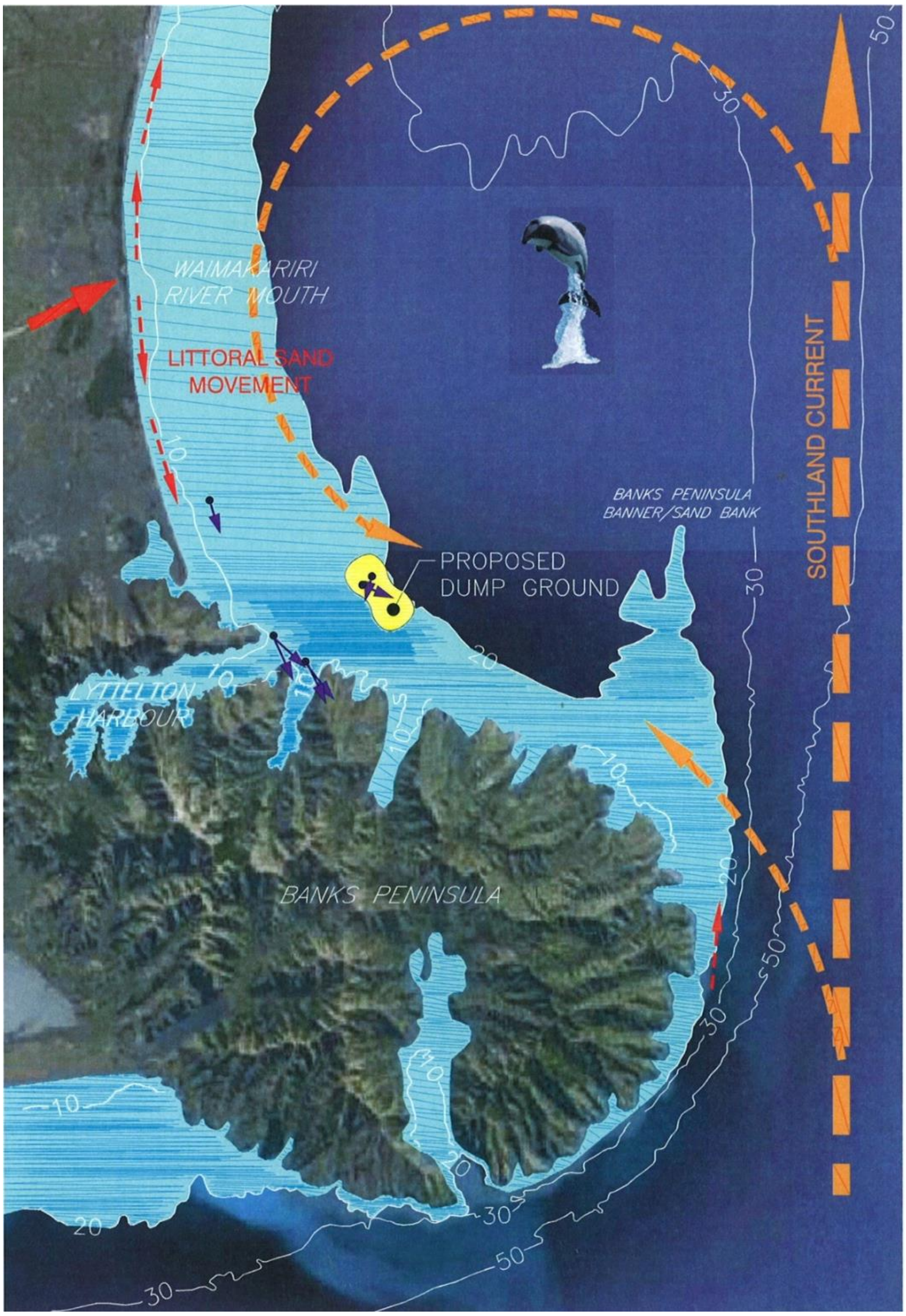


Figure No 1

3. Examination of the Pegasus Bay bathymetry shows that the continental shelf consists of two sections. The first is the near shore zone which extends to the 10 m contour and has a relatively steep gradient of approximately 1:65. The second, the offshore zone, is gently sloping with a gradient of approximately 1:1000. At about the 35 m contour the gradient steepens to the Pegasus Canyon which reaches a maximum depth of 1600 m.

4. The north setting flood tide is the stronger of the two tidal currents past Banks Peninsula and it reinforces the flow of the Southland current which runs up the east coast of the South Island.

5. Sea surface speeds of the Southland current within Pegasus Bay were calculated by Heath (1972) to be .07-.08 m/sec while according to Kirk (1979) the Southland current can attain velocities as high as 1 m/sec

(2 knots). Drift card data presented by Carter and Herzer (1979) suggested a much weaker flow with speeds in the order of .10-.15 m/sec.

6. The largest waves are from the south and south east and these waves can disturb the seabed of the continental shelf putting the silt and fine sand components into suspension. Once in suspension the sediment can move north around the flow obstruction represented by Banks Peninsula and drop out of suspension in the lee, in Pegasus Bay. The Southland current which forms a continuous but fluctuating eddy in the lee of the peninsula acts to distribute the sediment transported north across the inner continental shelf.

7. The banner bank is historic evidence of the transport of sediment north past the peninsula. LANDSAT satellite images have also shown plumes of discoloured seawater streaming north past the peninsula.

8. The LANDSAT photographs show two modes of behaviour for the current, as revealed by the tracer plumes of sediment, one where a counter clockwise eddy structure is seen within the bay and another where the northward moving flow persists within the bay (Carter and Herzer 1979). A LANDSAT photograph, reference Photograph No 2 shows sediment plumes north and south of Banks Peninsula with a sediment plume streaming north.

Photograph No 2

9. The seabed sediment in the Bay is derived from the same source as the loess mantling Banks Peninsula, the Southern Alps, consequently the mineralogy of the sediments is the same, they are indistinguishable.

3.0 DREDGING

1. The existing navigation channel will be deepened and extended by dredging to 17-18 m below Chart Datum (CD). Removing virgin seabed material rather than infill sediment is referred to as capital dredging, removing infill material is maintenance dredging. The capital dredging will also encompass deepening of the manoeuvring and berthing areas off and alongside Cashin Quay as well as some construction related dredging.

2. Maintenance dredging requires less mechanical effort than capital dredging because the infill material has a high natural moisture content and is close to fluid having been either deposited out of suspension or moved as bed load into the channel. The infill sediment has no inherent strength other than weak cohesion, acquiring it only through a process of natural consolidation under its own weight as the sediment accumulates and water is driven out. The maintenance dredging operation does not have to break the soil down to fluidise it and enable the material to be sucked up by a dredge pump.

3. Suction alone is not normally sufficient to entrain the virgin, undisturbed material, a cutter or ripper – tynes on the dredge draghead - is required to break it up to enable the soil to be drawn into the dredge pump. The Trailing Suction Hopper Dredge (TSHD) is suitable for both capital and maintenance dredging where the material to be dredged is relatively soft and suction dredging techniques can be employed. Only the size of the dredge changes. A large TSHD as used for capital dredging is shown in Photograph No 3.

Photograph No 3

4. The TSHD is a self propelled, self contained dredging vessel able to load, transport and dump dredged material unaided. It is the most productive and technologically advanced type of dredge and has a very wide application area. It is the principal workhorse of the dredging industry.

5. TSHDs are particularly efficient in dredging silts and sands, cause minimal disruption to vessels using the channel while dredging is in progress and have a relatively high rate of production the actual rate achieved being dependent on hopper size, round trip distance to the dump ground and the strength/hardness of the soil.

6. The TSHD sucks sediment off the seabed through one or more suction pipes trailing off the side of the vessel and discharges the sediment into the vessel's hold or hopper. The mouth of the suction pipe is fitted with a draghead that is dragged over the seabed while dredging, loosening/breaking up the seabed sediment allowing it to be ingested, sucked up, by centrifugal dredge pumps that provide the suction capacity. The draghead may be fitted with teeth/tynes, and or water jetting to assist in breaking up the material allowing it to be ingested and pumped up the trailing arm into the hopper.

7. Loading continues until the hopper is full at the target specific gravity of approximately 1.3. The output from the dredge pump is discharged overboard – giving rise to a minor sediment plume – until the desired specific gravity is attained at which point the discharge is directed into the hopper. For modern TSHDs the flow dumped overboard to obtain the desired specific gravity can be piped so that it either discharges under the vessel or back down the trailing arm to the seabed, minimising the sediment plume.

8. Once on the dump site location the TSHD opens the bottom doors of the hopper to discharge the hopper contents. The doors can either be hinged or sliding doors opened by hydraulic rams. Hinged doors are susceptible to damage when dumping in rough sea conditions. A split hull design can be used in which case the entire hull of the dredger is divided longitudinally in half and connected at deck level by heavy hinges. The Pelican has this configuration.

9. TSHDs can dredge in relatively rough seastate conditions particularly if the trailing arm is supported by a heave compensator device. There may be a restriction on the tolerable wave height in the dump location for split hull or hinged door vessels because of the high stresses on the hinges – the Pelican, a split hull vessel, has a 1 m wave height limit for dumping. The use of sliding bottom doors obviates this problem.

10. The draghead is one of the most important components of the dredge installation. It must be able to break the coherence of varied soil types. The excavation process is done by erosion, by water flow into the draghead, mechanically or by both methods. For optimum performance the type of draghead to be employed should be selected according to the type of material to be dredged.

11. An IHC type draghead or an active type draghead with rotating hydraulically powered cutters – both types illustrated ion Figure Nos 2 and 3 – is appropriate for use in medium, firm and stiff clays. Tynes/teeth or jets fitted to the underside of the draghead – Figure No 4 – will, in combination with the weight of the draghead, break up the hard layers, a task made easier by the layering of hard and soft material.

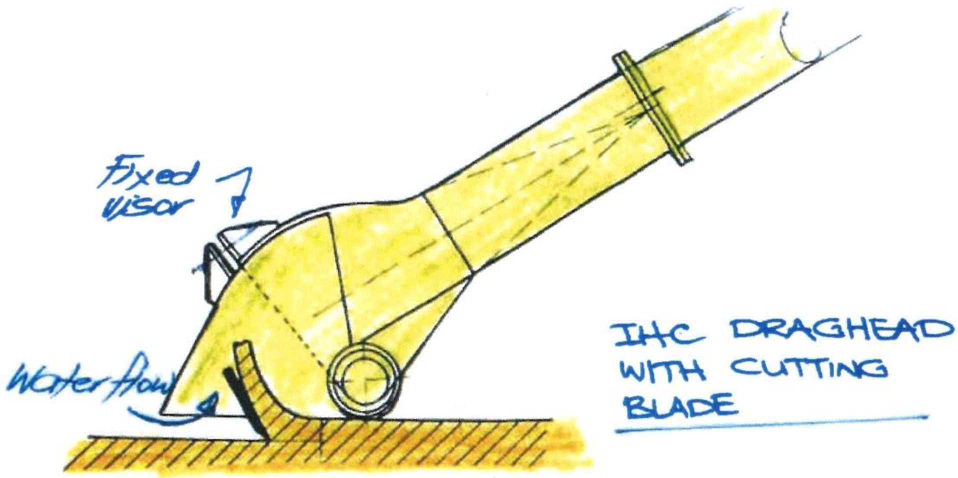


Figure No 2

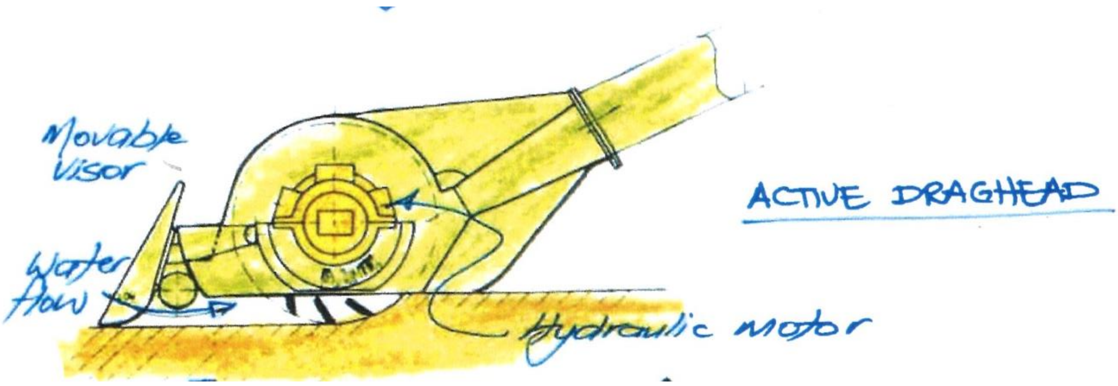


Figure No 3

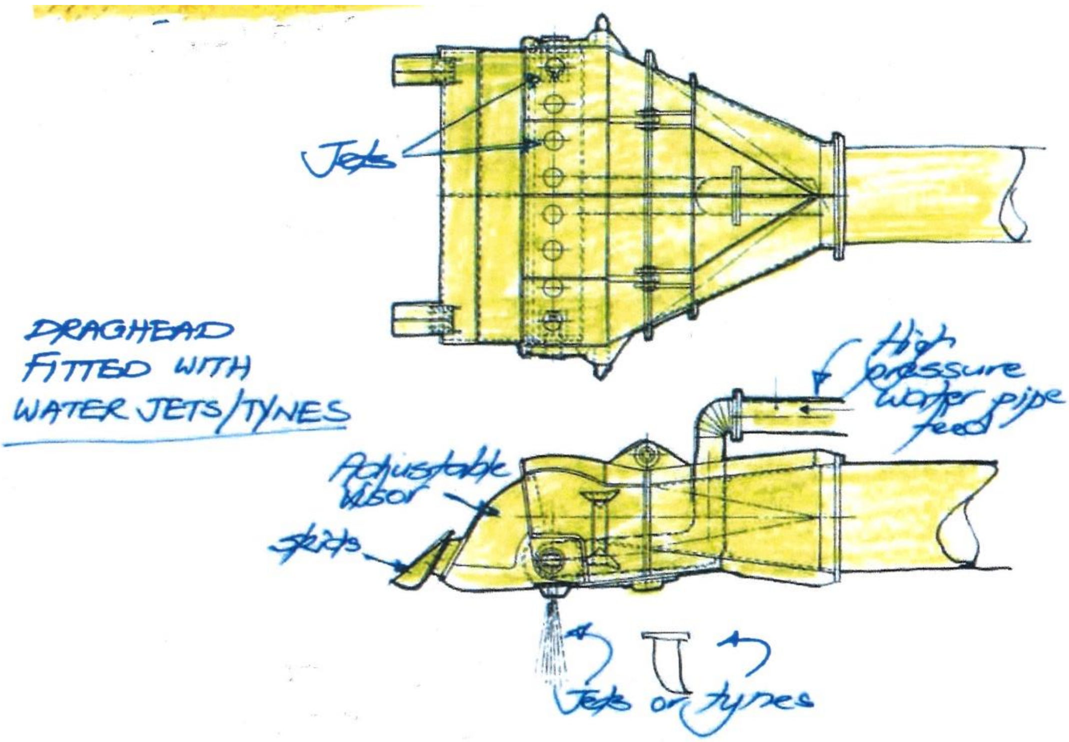


Figure No 4

3.1 Maintenance Dredging

1. Maintenance dredging is a major operating cost for LPC. Making it cost effective and reducing the need for it if possible is an important management objective. In the past the LPC predecessor organisation, the Lyttelton Harbour Board (LHB) owned its own dredges - Canterbury, Te Whaka and finally Peraki.

2. That was not cost effective with length downtime. Maintenance dredging is now undertaken under contract using small TSHB vessels, Pelican and New Era, approximately 900 m^3 hopper capacity, that undertake maintenance dredging at a number of NZ ports. Photograph No 4 shows the Pelican returning to the inner harbour.

3. A new, larger contract TSHB, approximately 1,850 m^3 hopper capacity is proposed to work on the NZ coast and undertake maintenance dredging work at 5 NZ ports.

4. The major sedimentary process within the harbour is the maintenance dredging program which removes in the order of 900,000 tonnes per year from the navigation channel. The dredged material is currently dumped within the harbour along the north side.

5. Prior to 1969 the sediment was dumped in the bays along the south side of the harbour. A study in the later 1960's, comparing plots of cumulative dumped volumes versus accumulated remaining seabed volumes for each bay indicated that the bays had reached capacity. The dumped volumes kept linearly increasing over time the accumulated seabed volumes levelled off indicating attainment of a notional capacity.

Photograph No 4

6. A change in dumping practice was implemented in 1969 in an effort to reduce wave energy passing up the harbour after wave refraction analyses showed the projected benefits of dumping dredged material to influence wave refraction. Dumping material on the side of the harbour to create a slope across the harbour causes the wave orthogonals to be directed towards the side of the harbour dispersing the energy over a wider wave front. The interest in reducing wave energy reaching the port developed after wave induced vessel motion problems were experienced following the opening of Cashin Quay.

7. The policy of dumping to maintain the wave refraction mounds has been abandoned in recent years following an analysis of the quantity of dredged material actually retained on the mounds over time – most of it has disappeared, recycled into the navigation channel. In addition the number of vessel motion incidents resulting in downtime is relatively minor.

8. Any dumping policy ideally endeavours to establish a balance between the two extremes of continuous dredging and dumping directly over the side - minimum dredge cycle time offset by maximum recycling - or dumping the sediment well outside the harbour so that none of it returns - long dredge cycle time offset by minimum recycling. The current dredging policy for the LPC is towards the minimum cycle time end of the dredging policy spectrum for a combination of cost and dredging efficiency reasons, however the bulk of the material dredged during maintenance dredging now goes to Godley Head.

9. The maintenance dredging of the navigation channel is presently carried out on contract by a trailing suction hopper dredge currently the New Era. The Pelican has also been used for this work. A description of the Pelican is contained in the Van Oord brochure attached as part of Appendix B. The Pelican and the New Era are similar in size, relatively small dredges compared to the size of vessel typically used for capital dredging. The new maintenance dredge intended to start later next year will have a capacity of 1,850 m^3. The hopper capacity for the Pelican is less than 1,000 m^3, the hopper capacity for a trailing suction dredge likely to be used for capital dredging at Lyttelton could be up to 18,000 m^3.

10. The channel is currently dredged for 1 to 2 months every year to clear the accumulated sediment. When the dredge has filled her hopper the vessel moves out of the channel and across to the designated dumping grounds on the north side of the harbour where the load is dumped by rotating the hull halves (Pelican) about a central axis to open the bottom of the hull. The hopper is emptied in a very short space of time. The cycle time for the dredge is typically of the order of half an hour.

11. The dredge track is readily apparent from the surface turbidity plume trailing behind the vessel. The plume consists of very fine material washed off the deck, overflow, the associated sediment volume is very low and rapidly dispersed by the eddies generated by the passage of the dredge. Photograph No 5 shows the turbidity plume behind the Pelican as it is dredging in the channel. This plume can be largely eliminated by discharging under the vessel.

Photograph No 5

12. The process of dredging reduces the sediment to a suspension which is pumped to the dredge's hopper. The sediment that accumulates in the channel is close to the fluid state so the transformation is minor but even the natural seabed material in Lyttelton Harbour is readily reduced to slurry. The normal efficient operation of a dredge such as the Pelican fluidises the sediment resulting in a suspension in which just 20% of the volume is solid material. The specific gravity of the suspension is then close to 1.3.

13. The tidal current monitoring work undertaken by OCEL in 2003 using the ADCP in the mobile mode showed that a tidal vortex develops inside Godley Head on the incoming tide and this vortex persists into the early stages of the outgoing tide, speeding up the outgoing tide in the region of Godley Head and producing a weak jet effect – reference Figure No 5 taken from that report.. This is of interest for flushing

sediment charged water out of the harbour. Figure No 5 is a snap shot at that point in time (3 hours after high tide) of the depth average velocity vectors in the outer harbour.

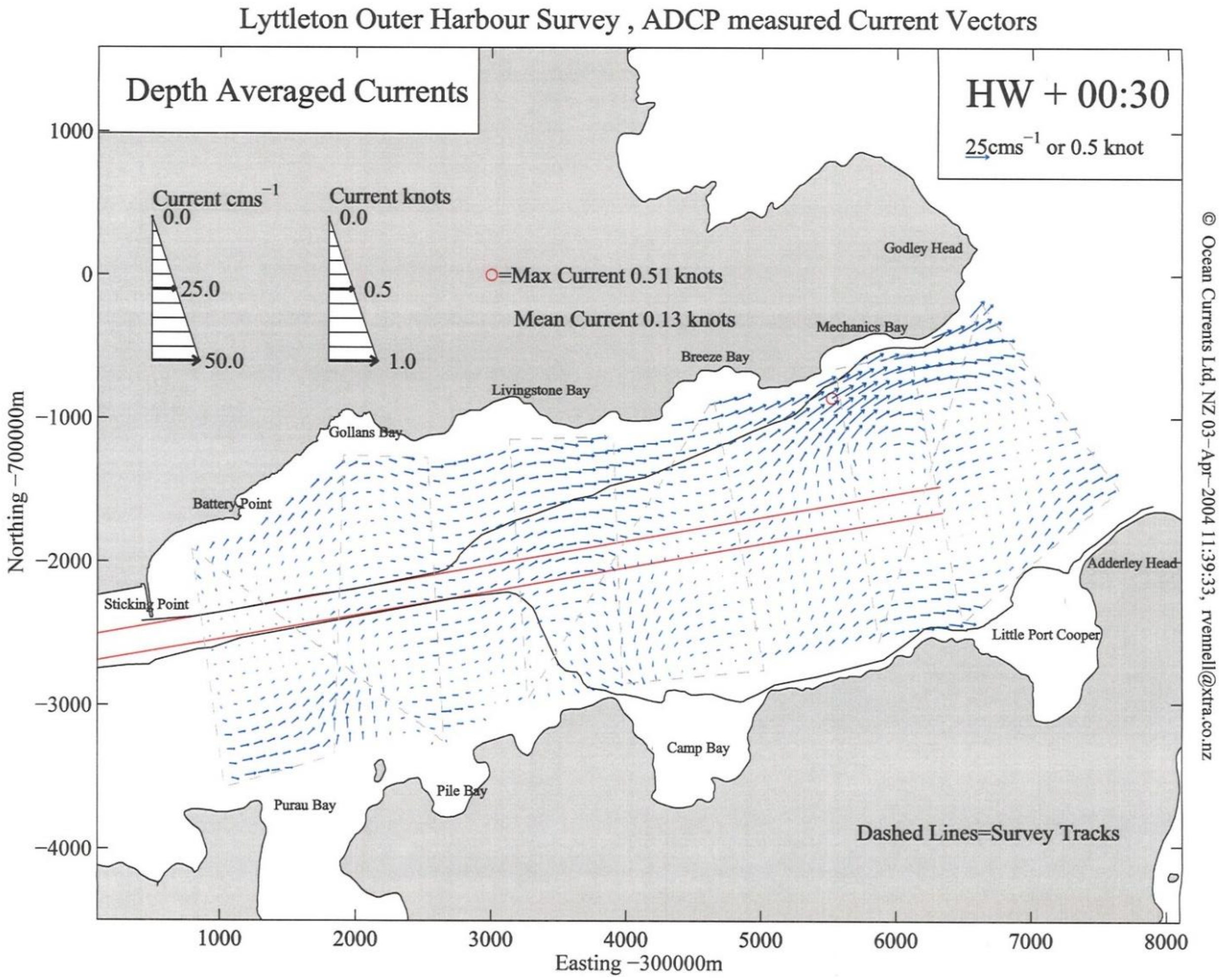


Figure No 5

14. The existing LPC resource consent covering the maintenance dredging work for the existing channel encompasses dredged material dumping locations along the north side of the harbour including an area inside Godley Head. Based on the identified tidal characteristics of the site this was identified as an attractive site for dumping the material dredged for the maintenance of the expanded channel since a significant proportion of the material dumped there would be flushed out of the harbour system and would not be recirculated.

15. The decision to dump material here was based on an understanding that of all the possible dump sites within the Heads this had the best potential to flush some material out of the harbour. There was no pretence that all the material would be flushed out because the tidal currents run in and out at this point. The tidal imbalance, the current runs out for longer than it runs in, would result in a greater proportion of material going out than in.

16. This decision was supported by the results of the Sediment Trend Analysis (STA) study – separately discussed in this report – which showed that fine sediment transport pathways were directed offshore from Godley Head.

17. To avoid any recycling of the dredged sediment which does occur at the Godley Head dump site all the sediment would have to be disposed of well offshore beyond the reach, excursion distance, of tidal

currents running into the harbour on the flood. To do this would significantly increase the dredge cycle time – time to pick up a load, dump it, and return to dredging.

18. More time would be spend in transit less in productively dredging. In addition there may be weather/seastate limitations on maintenance, dredges dumping out of the harbour. There were for the Pelican dumping was undertaken in seastates characterised by significant wave height H_s < 1 m. The proposed new dredge probably will not have these restrictions because of its different construction. It will be of a similar length, slightly longer, to the existing maintenance dredges so transit speed limitations will still apply.

19. As part of the work on the Godley Head locations the point to be covered by the 2007/2008 survey work, was to determine where the material flushed out of the harbour would travel to. The tidal current survey work undertaken for this report shows that the material flushed or 'pumped' out of the harbour would go out into Pegasus Bay in the weak jet off Godley Head. It does not head for the adjacent bays. The STA work showed that the fine sediment transport paths from Godley Head were out of the harbour sand size material went north along the coast.

20. For the extended channel it would make sense to utilise this dumping area for maintenance dredging (to minimise transit times) because it is close to the extended channel, turnaround times would be low, and a significant proportion of the material dumped there would be taken out of the harbour system on the ebb tide, not recirculated. Currently a location outside the harbour is being modelled by MSL the intent being to minimise/eliminate recirculation of material.

3.2 Channel Deepening Project Dredging

1. The seabed material dredged as part of the channel deepening will not be disposed of on the existing dumping grounds, it is not allowed under the existing resource consent and the volume to be disposed of represents many years of accumulated maintenance volumes.

2. The channel deepening dredging will be carried out by a much larger vessel than the dredge currently used for maintenance dredging. The dredge will be larger because the size is representative of a more cost effective dredging operation when the dumping location is further away. The size of the hopper will be much larger enabling a greater volume of material to be carried and the longer water line length allows a higher cruising speed, reducing the turnaround time.

3. If the vessel is using rippers on the drag head to break up the stiffer material at the bottom of the channel then the larger the vessel, and by extension the larger and heavier the drag head, the more power is available to break up the stiff material. A brochure for the Van Oord dredge Volvox Asia is included in Appendix B. The Volvox Asia is representative of the type of dredge that could perform the capital dredging work. The hopper capacity for the Volvox Asia is 10,800 m^3.

3.3 Alternative Dredging Methods

1. The discussion so far has only considered suction dredging. This is the type of dredging that has been used to dredge the channel from the time the channel was cut but is not the only way to carry out the dredging. An alternative way of dredging the harbour and a method available to the largest New Zealand dredging contractor, Heron Dredging, is to use a barge mounted excavator. Heron Dredging has two such dredges, the Kamahia and the Macheavelli, each one a specialized dredging unit. The Macheavelli was used offshore Christchurch to dredge the trench for the Christchurch ocean outfall.

2. The dredge consists of a barge fitted with spud piles and equipped with a large long reach hydraulic backhoe excavator that has an integrated computer controlled dredging system that enables the dredge operator to place the excavator bucket adjacent to the preceding pass. The dredge drops each bucket load into a hopper barge alongside. The barge sails away to the dump location once it has been filled. The production rate for such a dredge is much lower than for a trailing suction dredge – Photograph No

6 shows the Machiaveili on location for the installation of the Christchurch outfall in 2007. In this case the material dredged from the pipe trench was dropped into a hopper on deck then pumped 250 m away to the side of the vessel and discharged using a floating hose.

Photograph No 6

3. Another alternative is to use a cutter suction dredge, reference Photograph No 7. These dredges feature a hydraulically powered cutter on the end of a ladder. The dredge pump is often mounted on the end of the ladder as well to pump the dredged material up and onto a hopper barge alongside. The dredge holds position and swings laterally on a stern spud pile. The swinging, so that the cutter head moves in an arc, is accomplished by pulling on winch lines attached to anchors of the font of the dredge.

Photograph No 7

4. The drawback with this type of dredge is that it can create a large persistent surface plume. In areas where there is high natural turbidity such as Lyttelton it is less an environmental problem than a visual one. A cutter suction dredge is static and the plume builds around it.

5. A trailer suction dredge is mobile and its own motion helps to disperse the plume. The surface plume from a cutter suction dredge can be largely avoided if the dredge is used to break up the material then leave it on bottom to be picked up by a suction dredge. This is a more expensive operation and not warranted if, as in this case, the material to be dredged is relatively soft. The size and weight of the TSHB draghead for the capital dredge will break up stiff material.

6. The currently preferred option is to use a trailer suction hopper dredge.

4.0 DUMPING GROUNDS

4.1 Channel Deepening Project Dredging

1. The proposed dumping ground for the material dredged during CDP phase is located 4 nautical miles off the harbour entrance Heads in 20 m water depth – reference Figure No 6. If the upper limit quantity of sediment to be dredged, 18 million cubic metres, was deposited on the site the material would uniformly cover the site to an equivalent depth of approximately 1.5 m.

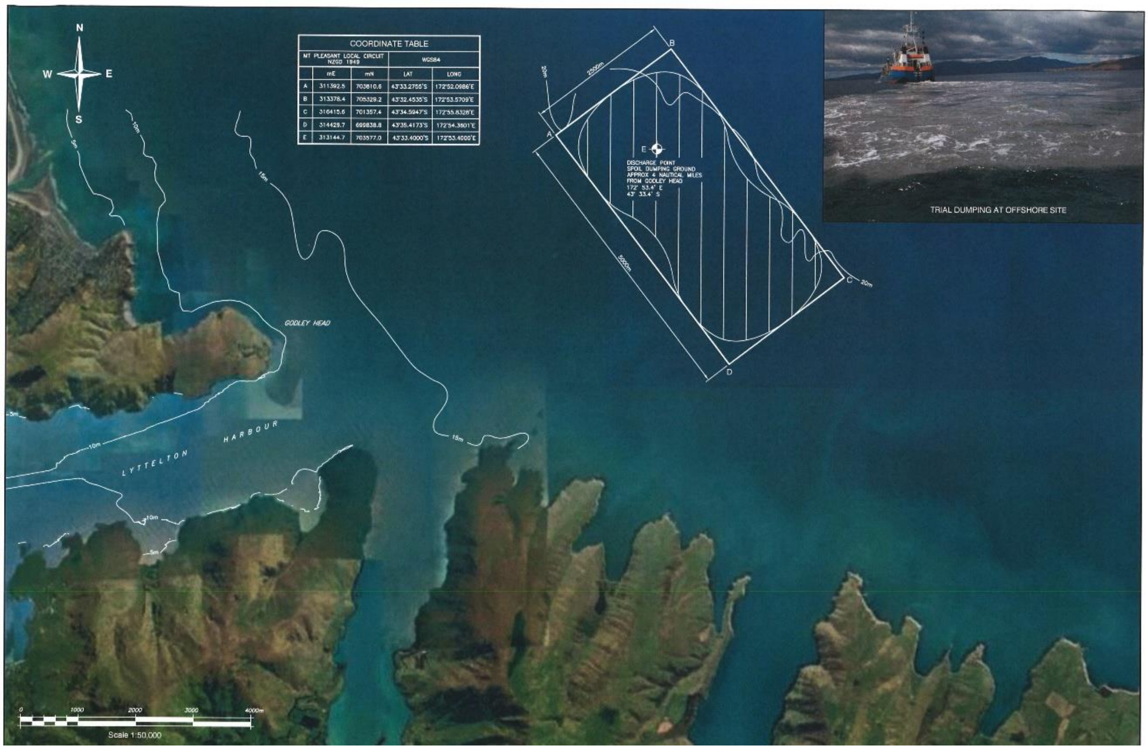


Figure No 6

2. The effects on wave refraction, shoaling height and navigation would be insignificant even assuming that all the material dumped there stays on location - it won't. As shown in the trial dumps of dredged material the material forms a dense fluid that is dispersed as a turbidity current when it impacts the seabed. The impetus or driving force for the turbidity current away from the dump location is provided by the denser fluid falling through the water column, potential energy is converted to kinetic energy. Because of the flat underwater slopes the potential energy or driving force is very much less.

3. Density currents are very important in producing the initial dispersion following dumping but of much less significance in distributing or transporting re-suspended sediment. Based on the dumping trials the turbidity current could move the sediment out to 300 m from the point of impact on the seabed. The resulting distribution won't be a circular deposition area unless the current is absent, more like an elliptical area the long axis of which coincides with the current direction. It can take up to an hour to travel the maximum travel distance for the edge of the plume so the current can move the material a considerable distance in that time before the concentration of sediment or turbidity decreases to the ambient level.

4. The harder material in the hard layer at the bottom of the existing channel will likely retain part of its structure in the form of chips that will survive passage through the dredge pump. These chips will gather close to the impact point on the seabed for each dump, dispersed radially about the impact point, but will not amount to a significant proportion of the volume of each dump.

5. A similar accumulation of chips was found at the dump site for the trial dumping in 2003 when an attempt was made to measure the volume remaining. The volume was determined at less than 20%, contained within a circular area of 20 m diameter centred on the dump point. This is only the initial figure before wave action acts to entrain the material into suspension and re-distribute it.

4.2 Maintenance Dredging

1. The existing maintenance dredge disposal locations close to Godley Head are covered by an existing consent and will be retained. The existing consent is not applicable for the deepened channel but it may remain in use for inner harbour dredge spoil. It may also be used to dump maintenance dredging material if the dredge cannot access the offshore dump site on account of the prevailing seastate although the introduction of a new TSHD for maintenance will reduce weather sensitivity.

2. Irrespective of where the dredged material is disposed of along the north side of the harbour, as in recent years, it will be recirculated back into the channel at some point as the material is swept back and forth on the tide – reference the work by Mulgor (2013) on neutrally buoyant particle trajectories over a number of tidal cycles. Because of the tidal current asymmetry and the weak vortex jet at Godley Head a significant proportion of sediment dumped at the location will go offshore on the outgoing tide and escape the harbour system. This was the basis for choosing the location, along with considerations of dredging productivity and the seastate operational limits (dumping) for the small existing contract dredgers, New Era and Pelican. The dump location has been a compromise – where is the best location with the highest probability of material leaving the harbour while simultaneously allowing maximum productivity and minimum downtime for the maintenance TSHD's that have been working the NZ coast. That location was determined as Godley Head.

3. To avoid any chance of the dumped material recirculating back in the harbour and settling out in the channel the dredged material needs to be dumped beyond the reach of the harbour. The LPC is currently proposing a new dump location for the maintenance dredging material approximately midway between the capital dredge dumping ground and Godley Head as part of the CDP consent. MSL are currently modelling potential locations. The introduction of a larger less weather sensitive TSHD for maintenance dredging work around NZ makes the offshore location a more practical proposition.

4. Even if all the material dredged as part of the maintenance dredging operation were to be taken out of the harbour system this would not stop the infilling of the channel because the whole harbour bed can be disturbed by wave action in a swell event putting the sediment into suspension where it can be moved by tidal currents. These tidal currents are deflected across the line of the channel for both the incoming and outgoing tides and the channel acts as sediment trap for the suspended material. The harbour regime system attempts to return to the dynamic equilibrium flat seabed condition by filling in any depressions (channels) in the seabed.

   Over time however if material is dumped outside the reach of the harbour it would be expected that the volume of maintenance dredging material dredged annually would decrease in the long term because there will be less fluid material in the harbour.

5.0 THE NATURE OF THE MATERIAL TO BE DREDGED

5.1 Sediment Description

1. The sediment to be dredged as part of the CDP work is predominantly (60%) silt size sediment derived from the loess that mantles the catchment area. There is however a hard layer at the bottom of the existing channel that will need to be removed as part of the deepening process. This layer consists of alternating layers of stiff sandy silt material.

2. The harbour seabed sediment can be generally categorised as a very fine clay silt mixture with an in situ density of 17 kN/m^3. A typical sediment size analysis of the sediment shows the particle size distribution and Atterberg limits as:

• Fine Sand (0.25 to 0.05 mm)	1%
• Silt (0.05 to 0.005 mm)	45%
• Clay (smaller than 0.005 mm)	54%
• Liquid Limit LL	30 - 45
• Plastic Limit PL	20 - 30
• Plasticity Index PI	10 - 15

3. Outside the Heads the material changes more to a fine sandy silt with the silt fraction predominant. Typical shear strengths range from 10 kPa at the seabed to 50 kPa at the dredged depth limit.

4. The fine sand component increases with distance offshore. Further out in Pegasus Bay the seabed consists of dense fine sand overlain by a fluid mud layer.

5. As part of the geotechnical investigation work undertaken by OCEL for the CDP work core samples were collected along the centreline length of the channel, and the proposed extension. Complete cores were obtained in the channel hard bottom area. Representative samples were selected for particle size distribution (PSD) analysis from the cores. A particular interest was in obtaining samples from the hard layers.

6. The results of the PSD analysis for the selected cores expressed in terms of the percentages of fine sand, silt and clay are given in Table No 1, along with the typical PSD given in 2.0 above. There was surprising little difference between the composition of the hard and soft layers, with nothing to identify the layers from a simple comparison of the PSDs. The sample IDs are as shown on Drawing No DR-030901-013 attached as Appendix A.

CHANNEL CENTRELINE PARTICLE SIZE DISTRIBUTION				
SAMPLE ID	SAMPLE DEPTH	FINE SAND % .25 to .05 mm	SILT % 0.05 to .005 mm	CLAY % Smaller than .005 mm
Typical - surface	Surface	1	45	54
24	4.2-4.4	3	59	38
26	2.80-3.10	19	51	30
27	1.3--1.60	11	54	35
28	4.00-4.30	13	54	33
31	2.00-2.30	10	66	24
51	2.50-2.80	10	61	29
56	1.40-1.70	6	60	34
58	1.10-1.50	15	65	20
58	2.60-3.50	5	64	31
58	4.60-5.15	2	63	35
59	1.70-2.00	5	63	32
61	0.30-0.50	3	63	34
61	1.30-1.50	12	58	30
2A	Surface	4	70	26
4	3.00-3.30	1	52	47
4	3.90-4.20	1	54	45
4	5.00-5.30	2	60	38
11	5.50-5.80	1	57	42
14	1.70-2.00	1	51	48
14	4.50-4.80	1	57	42
15	3.80-4.10	5	53	42
16	2.50-2.80	1	57	42
16	5.50-5.80	1	51	48
18	3.00-3.30	2	56	42

Table No 1

7. The bulk of the dredged material is then quite similar in composition, but with a higher fine sand content, to the material dredged out of the existing channel as part of the maintenance dredging operation.

5.2 Geotechnical Investigation

5.2.1 Hard Layer

1. The depth of the existing navigation channel is approximately 12.2 m below CD.

2. A hard layer was long known to exist at the bottom of this channel however the exact nature of the layer was not known.. The drag heads of the previous LHB dredges Canterbury and Peraki periodically bounced off the top of this layer in the section of the channel off Camp Bay during the course of dredging operations over the years.

3. The layer is quite distinct, a definite transition from soft silt to very hard material, and was initially identified as rock. It does not occur within the dredged depth of the existing channel but will be encountered during CDP.

4. The hard layer has been investigated, by OCEL, in two distinct phases or campaigns, separated by a number of years. The focus of the initial investigation work in 2004 was to determine the nature of the hard layer and its strength – shear strength for cohesive material friction angle φ for non cohesive.

5. The second phase of the investigation work was undertaken in 2015-2016 and was not confined just to the hard layer. The intent of the work, specifically undertaken for the capital dredging work was to

characterise the nature of the seabed material to be dredged during the CDP along the full length of the existing channel and the proposed extension. This included investigations of the hard layer.

6. A total of 48 investigation locations were employed based on a channel centreline spacing of 250 m. These locations and the types of tests undertaken at each location are shown in Drawing No DR-030901-013. The boreholes and test locations for the first phase of the OCEL investigation work are also shown.

7. The number of site investigation locations – the intensity of the investigation work – required to characterise the nature of the material to be dredged as part of the CDP was determined on the basis of the Permanent International Association of Navigation Congress (PIANC) recommendations contained in the PIANC publication 'Site Investigation Requirements for Dredging Waters'.

5.2.2 Initial Investigation 2004

1. The initial geotechnical investigation work which was specifically undertaken anticipating an extension to, and the deepening of, the channel included water jet probing and sediment sampling along the centreline of the existing navigation channel and beyond and drilling through the hard layer to gain further information on its composition. A diver operated shear vane was also used in an attempt to gain in situ shear strength information but was unsuccessful – the layer was too hard.

2. The water jet probing was undertaken to establish the top channel centreline profile of the layer. The results of the water jet probing are shown on the attached Drawing No DR-030901-013 – Appendix A. Probing was carried out at close to 250 m centres along the channel centreline from just inside the Cashin Quay breakwater to the start of the existing channel off Camp Bay, a distance of 4.5 km.

3. The bottom of the channel and the natural seabed out beyond the end of the existing channel were taken as the reference depth for the probing and the probe penetration distance measured down from there. The hard layer was shown to exist along the length of the channel, at varying depths from the bottom of the dredged channel but always outside the existing dredged depth. The minimum depth to the layer was 0.7 m off Camp Bay. Out beyond of the existing channel the layer dropped off and became softer, able to be penetrated by the water jet probe.

4. Because it was not possible to penetrate the hard layer with a sampling tube or a shear vane OCEL's underwater Standard Penetration Test (SPT) rig – see Photograph Nos 8 and 9 - was used to obtain SPT N values for the top of the hard layer. The SPT consists of driving a standard split-barrel sampler a total distance of 18" into the bottom of the borehole using a 140 lb (63.5 kg) hammer dropped through a height of 30" (762 mm). The imperial system measurements reflect the American origins of the test. The number of blows required to drive the sampler each increment of 150 mm of a total drive distance of 450 mm are recorded. The N value is the sum of the number of blows required to drive the last 300 mm.

Photograph No 8

Photograph No 9

5. The SPT locations are also shown on Drawing No DR-030901-013. The SPT No recorded for SPT location No 1 is 16, the SPT number for SPT location No 2 was 14. These numbers constitute the raw data. The standard test is carried out in air, corrections are therefore required to allow for the submerged weight of the SPT hammer and the hydrodynamic drag generated as the weight drops through water since both these effects result in a decrease in the impact energy applied to the hammer anvil. Applying a correction for the energy loss consequent on submergence the N values obtained for the SPT locations are – SPT1 N = 12, SPT2 N= 10.

6. A check on the actual submerged hammer impact energy developed by the underwater SPT equipment hammer was undertaken in 2014 following geotechnical investigation survey work at the site of the proposed Kaheru well location offshore Taranaki prior to the arrival of the jackup drill rig on site. The objective of the test was to verify the impact energy ratio figure (83%) derived by calculation.

7. The test was undertaken by placing two lead cylinders diametrically opposite and directly underneath the submerged hammer and dropping the hammer 762 mm in water. The dimensions of the two deformed compressed cylinders were then compared with two identical cylinders placed under a standard SPT hammer and subject to a 762 mm drop in air. Both sets of deformed cylinders were identical indicating that the energy impact figure were the same for both the standard and modified underwater rig – no correction is required.

8. The SPT N values correlate with soil strength parameters - q_u the unconfined compression strength and c_u the undrained soil strength for cohesive soils – of interest for dredging. The soil strength parameters are used to assess the dredgeability of the material. The channel seabed is easily dredged by a suction dredger equipped with a cutter or rippers, the question is what sort of production rate can be achieved? Based on the corrected N values the material was classified as stiff with an unconfined compressive strength, q_u, ranging from 100 to 200 kPa. These values are for the top of the hard layer.

9. The stiff sandy silt material identified as constituting the hard layer at the bottom of the channel is closely similar to the stiff sandy silt and silty sand bands identified in the geotechnical boreholes established for the CQ3 and CQ4 berths. A 6 m thick band of alternating sandy silt and silty sand layers is shown in the borehole log for the CQ4 borehole intersecting the soft clayey silt between 22.9 and 28.9 m below Harbour Datum. The mineralogy of the hard layers is the same as for the other harbour seabed sediment.

10. The band of stiff material is underlain by soft grey clayey silt. Triaxial test shear strength results on recovered samples and in situ shear vane results are available for these layers. The design shear strength for the design of the CQ4 piles was taken at c_u = 120 kPa, the values obtained from the triaxial testing. The highest shear vane reading obtained, before the shear vane broke, indicated a shear strength of 200 kPa.

11. The shear vane values need to be corrected by applying a reduction factor λ ($s_{udesign} = \lambda\ s_{uv}$), directly related to the soil plasticity index, but were still higher than the triaxial values. The lower values were conservatively taken for the pile design. The material in the layers identified in the CQ3 and CQ4 boreholes appears closely similar but occurs at a deeper depth than the channel material.

12. The samples recovered from the SPT sampling spoon were identified as very stiff sandy silt, cohesive material, and were very hard to deform by hand squeezing and too hard to allow the use of a Torvane (mini shear vane) to determine in situ shear strengths.

13. The diver assisted investigation work identified the top of the hard layer but gave no indication as to the possible depth of the layer. Subsequent to the initial subsea investigation work OCEL provided the marine support for a geophysical investigation using boomer equipment (high resolution continuous seismic reflection gear) to determine the nature of the seabed along the line of the proposed Christchurch City Council (CCC) ocean outfall.

14. While that equipment was mobilised and on board the OCEL survey boat the opportunity was taken to deploy the equipment for a run along the channel centreline on the return to the harbour from the CCC outfall work. The output clearly identified the hard layer (very hard acoustically), identified constituent sand/silt layers within the hard layer and indicated a variable depth for the hard layer up to 6 m thick. Off the entrance to Purau Bay a channel was evident in the record indicating possible ancient river flow out of the Bay.

15. Figure Nos 7 and 8 attached are interpretations of the Boomer seismic reflection profiles. The profile comprises an essential flat to shallow sloping seabed that has no rugged topography associated with it. Below the seabed is a typically thin (<1 m to 6 m) unit of recent (Holocene) very soft silt and clay. This unit sits over a discreet horizon, typically 2 m to 6 m thick, of stiff to hard sandy silt. The top of this unit (base of the surficial unit) has a typically rugged to undulating topography, indicating that it may be a palaeo-surface, possibly associated with the Last Glacial Maximum. Likewise the base of this unit is also rugged and often very hard to discern from the seismic record.

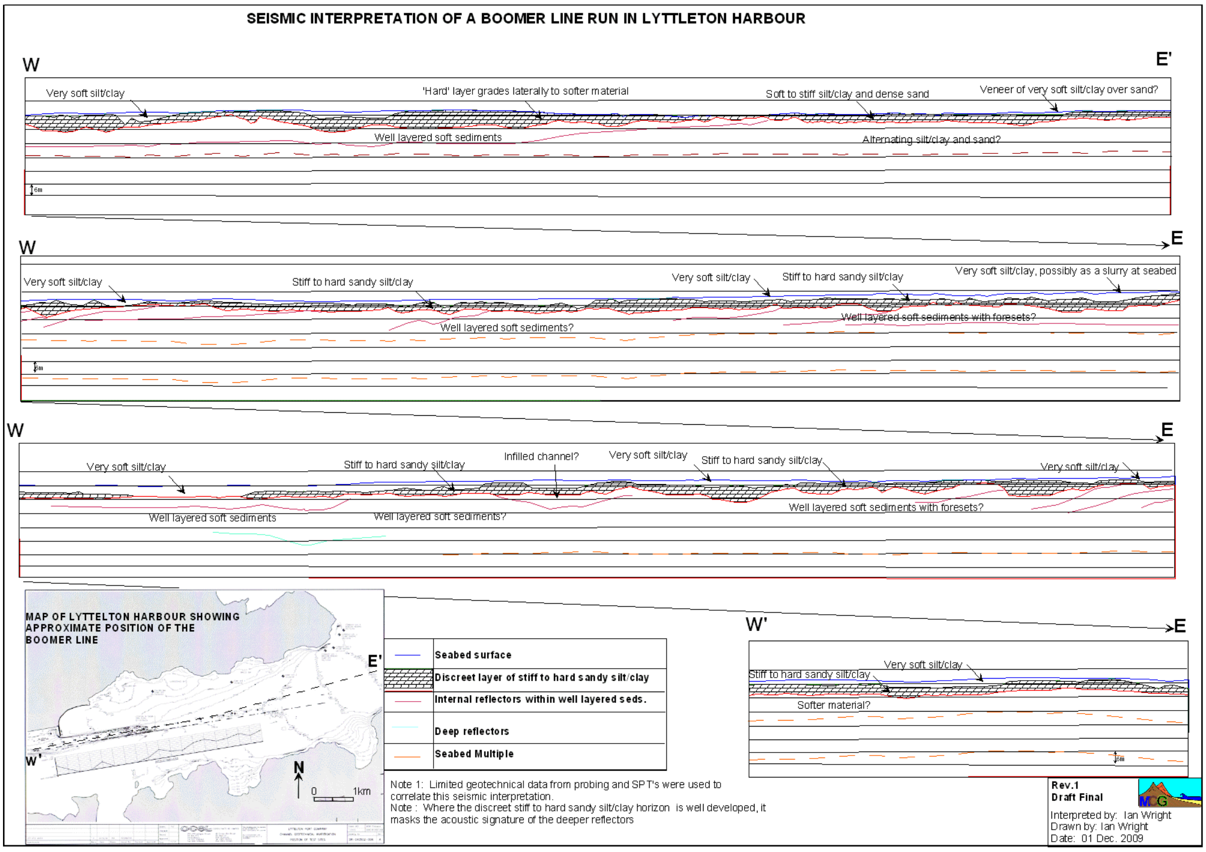

SEISMIC INTERPRETATION OF A BOOMER LINE RUN IN LYTTLETON HARBOUR
W
E'
Very soft silt/clay
'Hard' layer grades laterally to softer material
Soft to stiff silt/clay and dense sand
Veneer of very soft silt/clay over sand?
Well layered soft sediments
Alternating silt/clay and sand?
W
E
Very soft silt/clay
Stiff to hard sandy silt/clay
Very soft silt/clay
Stiff to hard sandy silt/clay
Very soft silt/clay, possibly as a slurry at seabed
Well layered soft sediments?
Well layered soft sediments with foresets?
W
E
Very soft silt/clay
Stiff to hard sandy silt/clay
Infilled channel?
Very soft silt/clay
Stiff to hard sandy silt/clay
Very soft silt/clay
Well layered soft sediments
Well layered soft sediments?
Well layered soft sediments with foresets?
MAP OF LYTTELTON HARBOUR SHOWING APPROXIMATE POSITION OF THE BOOMER LINE
E'
W'
N
0
1km
Seabed surface
Discreet layer of stiff to hard sandy silt/clay
Internal reflectors within well layered seds.
Deep reflectors
Seabed Multiple
W'
E
Very soft silt/clay
Stiff to hard sandy silt/clay
Softer material?
Note 1: Limited geotechnical data from probing and SPT's were used to correlate this seismic interpretation.
Note : Where the discreet stiff to hard sandy silt/clay horizon is well developed, it masks the acoustic signature of the deeper reflectors
Rev.1
Draft Final
Interpreted by: Ian Wright
Drawn by: Ian Wright
Date: 01 Dec. 2009

Figure No 7

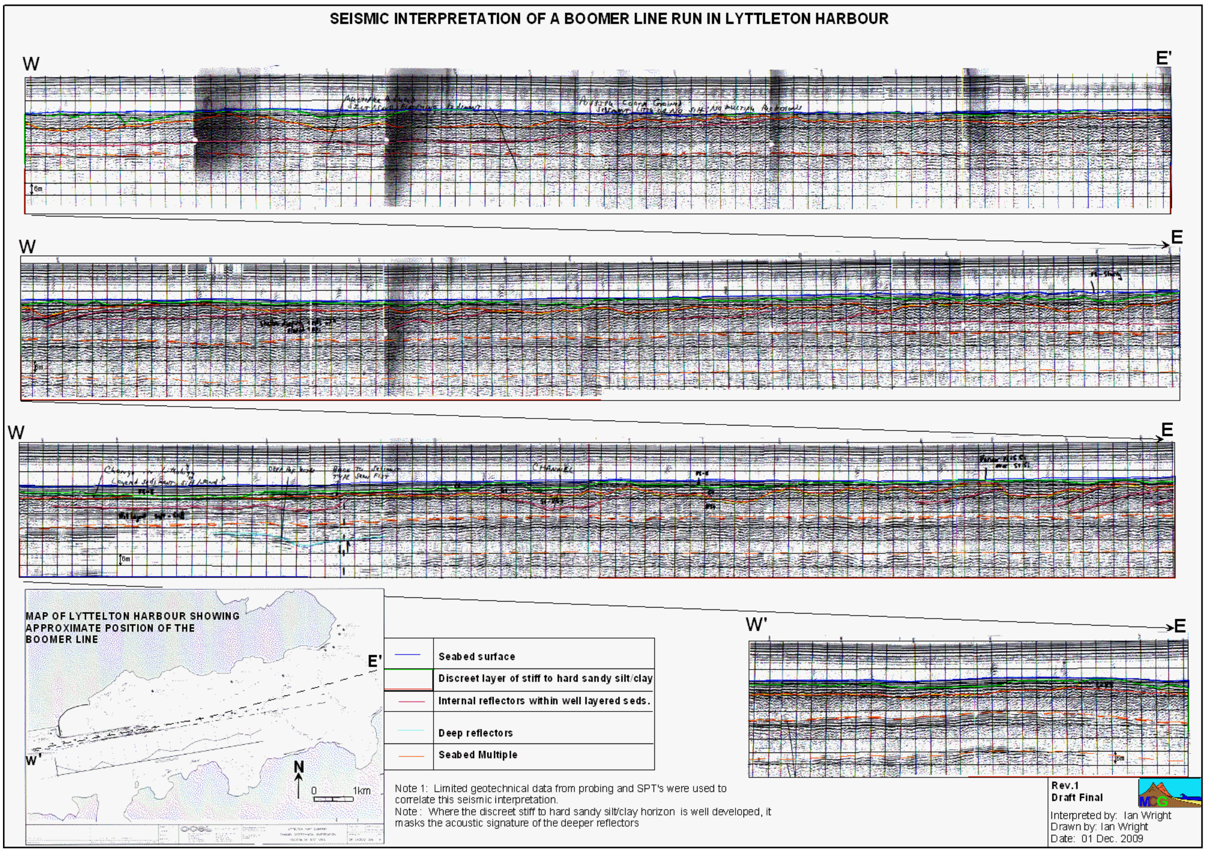


Figure No 8

16. The units underlying the discrete stiff to hard horizontal are difficult to resolve where the overlying horizon is well developed (harder). This is because the hard material reflects most of the acoustic energy. However, there are a number of places where the discreet horizon is less well developed. These areas provide a 'window' into the lower horizons. These windows (together with limited geotechnical sampling) indicate that the material below the discrete stiff to hard horizon comprises a thick unit of layered, typically soft, material. Weakly resolved 'foresets' that dip to the west are also located within this massive unit. This internal structure dips the 'wrong way' for the units to be interpreted as a typical delta front that is growing seaward and as such the origin of these sediments remains unresolved.

17. Quite how the dense layers come to be underlain by soft sediment is not clear but it is possible that the discreet stiff to hard horizon was exposed sub aerially (above water) during the Last Glacial Maximum and may be a palaeosol (ancient soil) horizon that has undergone substantial induration (hardening) during this period. This would explain why a harder horizon is found over softer, typically shallow marine, material. It should be noted that the Boomer is a seismic reflection device and as such cannot provide details of material under a 'hard' horizon that reflects most of its energy.

18. Given the similarity between the sediment recovered from the hard layer in the channel and the stiff dense material recovered from depth in the CQ4 borehole an attempt was made to link the two layers by continuing the transit of the survey boat past the Cashin Quay breakwater and in to the face of the Cashin Quay container berths. The presence of moored vessels however caused interference to the acoustic reflections and in any event the channel layer faded before the end of the Cashin Quay breakwater was reached, the strata becoming broken up suggesting turbulence from wave action as opposed to the calmer conditions in which the layers observed further seaward along the channel were laid down.

19. It did appear, from the analysis of the output, that the channel layer was similar to the layer under Cashin Quay, each layer consisting of alternating bands of dense sandy silt or silty sand, the bands sandwiched by the soft grey clayey silt characteristic of the harbour seabed. There was no apparent link between the

layer in the channel and the layer under Cashin Quay and none really expected because of the close to horizontal nature of the both layers and the difference in depth.

20. During the investigation work carried out for the channel extension and deepening a diver operated, purpose built, lightweight subsea drill rig shown strapped to the side of the dive support vessel in Photograph No 10, was used to drill a hole through the top 4 m of the hard layer at the location shown on Drawing No DR-030901-013. The drilling operation confirmed that the hard layer was a series of thin silty sand layers interspersed with soft silt material. At the location drilled two hard layers less than 1 m thick were encountered in 4 m drilled depth with soft silt in between.

Photograph No 10

5.2.3 CDP Investigation 2015-2016

1. The geotechnical investigation work undertaken in 2015-2016 was informed by the results of the earlier work and specifically directed at characterising the nature of the material to be dredged for the dredging contract. It was not confined just to the hard layer.

2. Based on OCEL's knowledge of the harbour and involvement on previous investigation work – test bores for the design of CQ3 and CQ4, investigation of the hard layer at the bottom of the existing channel and additional CPT, geophysical, and shear vane investigation work in the harbour both for the Christchurch City Council (CCC) (marina and submarine pipeline investigations) and the LPC – the investigation methodology decided on was the use of diver operated shear vanes and core sampling gear to collect in situ strength data and core samples along the full length of the navigation channel and its proposed extension.

3. Over the length of the channel that had previously been identified as having a hard layer just below the current dredged depth core samples were collected using diverless drilling equipment operated off a workboat. The hard layer had previously been investigated, by OCEL, using subsea drilling gear and an underwater SPT rig. The intent of the coring was both to identify the nature of the layers and capture cores of the hard material, silt/sand, that could be subjected to unconfined compression testing.

4. The drilling gear consisted of a purpose built coring tool which was driven diverless by the suitably modified top drive unit used for a subsea screw anchor installation tool. The installation tool shown in

Photograph Nos 11 and 12 essentially consists of a hydraulic motor and gearbox mounted centrally on a torque resistance arm which runs down constant tension guidelines run from a stern A frame on the work boat. The guidelines are tensioned against 1 tonne lead weights, reference Photograph No 11. The torque developed by the hydraulic motor is resisted by horizontal reactions against the constant tension wires at either end of the installation tool arm.

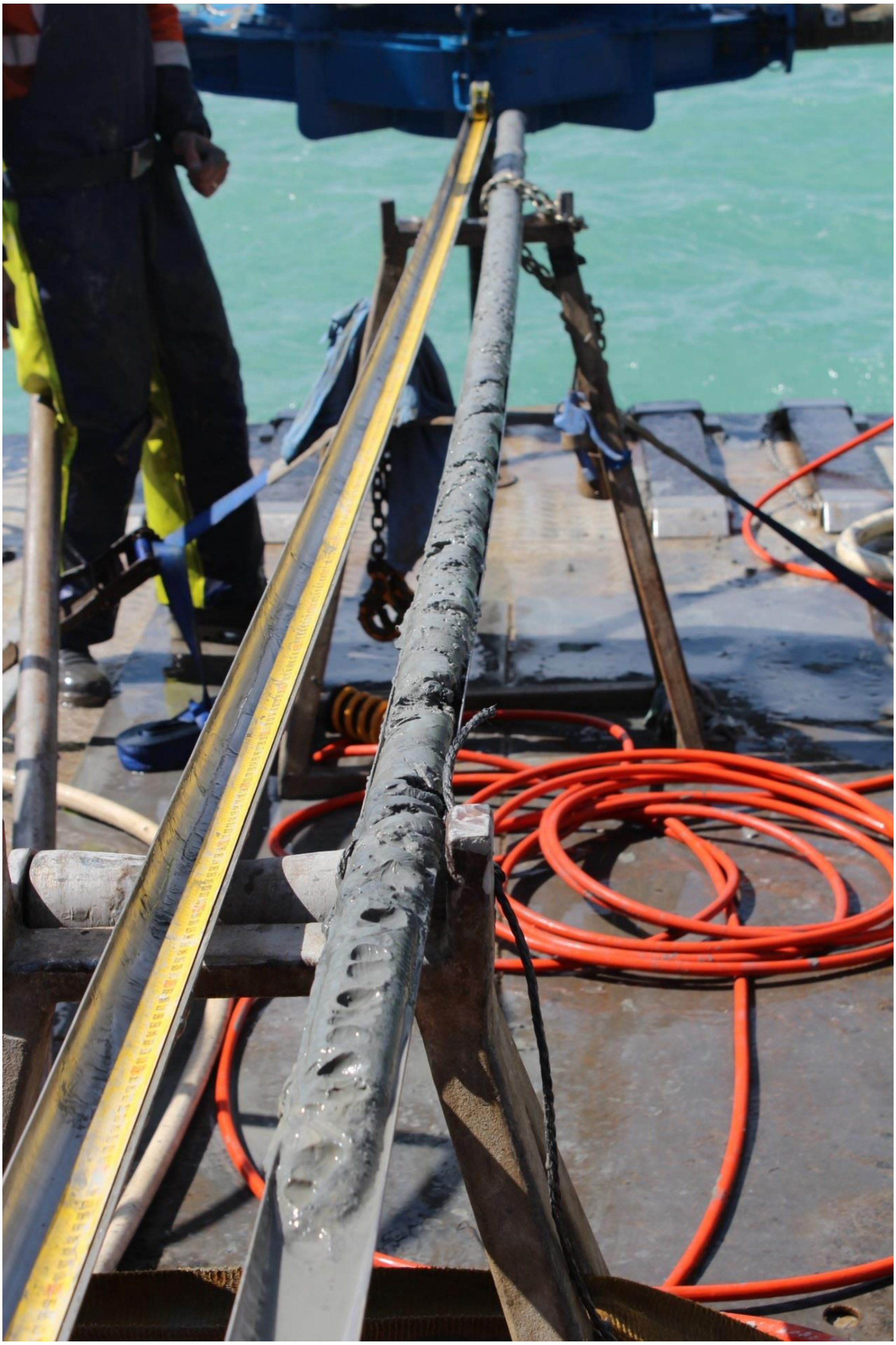
Photograph No 11

Photograph No 12

5. For the geotechnical investigation work the drive shaft was replaced by a split sampling tube inside a core barrel contained within a casing fitted with a drilling shoe, all standard components adapted for the task and supplied by Blick Industrial Limited. High pressure water was pumped down the annulus between the casing and the core barrel to clear the drilling bit. The outside of the casing was fitted with a continuous auger to drive this tool into the seabed.

6. The drilling tool proved capable of obtaining cores up to 6 m long both in area of the channel where the hard bottom occurred and beyond that in the soft silt material. Because of its success in recovering full core lengths in soft sediment its use was extended to those areas beyond the hard bottom section of the channel where penetration to 4 m into the seabed was required.

7. The tool successfully sampled the hard area and complete, 95%, cores in excess of 4 m length were obtained, Photograph No 13. Photograph No 14 shows the plasticity of the soft normally consolidated material. However while layering was apparent in the recovered cores, alternating thin, stiff and soft layers as expected, the stiff material was not hard and had apparently been remoulded by the drilling operation. It was not then possible to extract compact cylinders for unconfined compression testing as had been anticipated. The ease with which the material was remoulded is encouraging for the dredging process. The material is sensitive and a large draghead should readily remould it and ingest it.



Photograph No 13

Photograph No 14

8. On the basis of the stiff material exposed in the recovered core it should have been possible to push in a shear vane into it. Follow up dive inspections confirmed that pushing a shear vane into the hard on bottom material was not possible. The top of the hard layer is undulating, as shown by the seismic runs and the hardness varies but not to the point where a shear vane could be pushed into it.

9. A diver operated subsea drilling rig that replicated the rig used in the earlier investigation work was developed and used to obtain core samples at a number of test locations close to where the hard layer is closest to the existing dredged depth in the vicinity of location 13. The subsea drilling rig was not able to consistently capture complete cores showing the alternating layers of soft and hard material but relatively hard cores were obtained. The maximum shear strength for the recovered cores was 100 kPa.

10. While the coring tool successfully cored the locations in the hard channel bottom area it was not possible to relate the observed layering to strength values. The diver operated subsea drilling rig was able to yield soil strengths but was not able to capture a continuous profile, softer material was lost on recovery.

11. The lack of detailed knowledge of the layering and associated strengths in the hard area could potentially render the LPC vulnerable to additional work claims from a large well resourced dredging contractor. The claims would relate to actual productivity achieved as opposed to that allowed for on the basis of the geotechnical information supplied. A capital TSHD will be able to deal with the material identified the only question is at what rate.

12. The most effective way to gather continuous soil profile information is to use a cone penetrometer test (CPT) device which is forced into the seabed sediment at a constant rate of between 1.5 – 2.5 cm/sec. The cone is a sophisticated piezo electric device that can measure the tip pressure and pore water pressure. A range of soil data can be obtained from interpretation of the results but it is not sufficient by itself to fully describe the seabed sediment. It needs to be calibrated against a borehole and actual soil

samples. The device produces a penetration record not actual soil samples. In the case of the LPC channel borehole data and undrained shear strength values are available from OCEL's work. The CPT data could be gathered from intermediate or fill in locations between the OCEL test locations with one of two CPT locations being at the same position as the OCEL test locations for the purpose of calibrating the CPT data. A CPT rig will be deployed from the Heron Dredging pickup barge Tuhura currently under contract to the LPC to gather the continuous profile data in the hard area.

6.0 NATURE OF THE DUMPED MATERIAL

6.1 Fluid Nature

1. While the dredged material that accumulates in the dredge hopper is typically thought of as a solid material the reality is that it is more in the nature of a dense fluid (with some small differences between maintenance dredge spoil and the CDP dredge spoil discussed below). Photograph No.15 shows the fluid nature of the dredged material filling the hopper of the dredge New Era. When the contents of the dredge's hopper are dumped it is less a matter of dropping solid material through the water column rather than releasing a dense fluid into a less dense on.

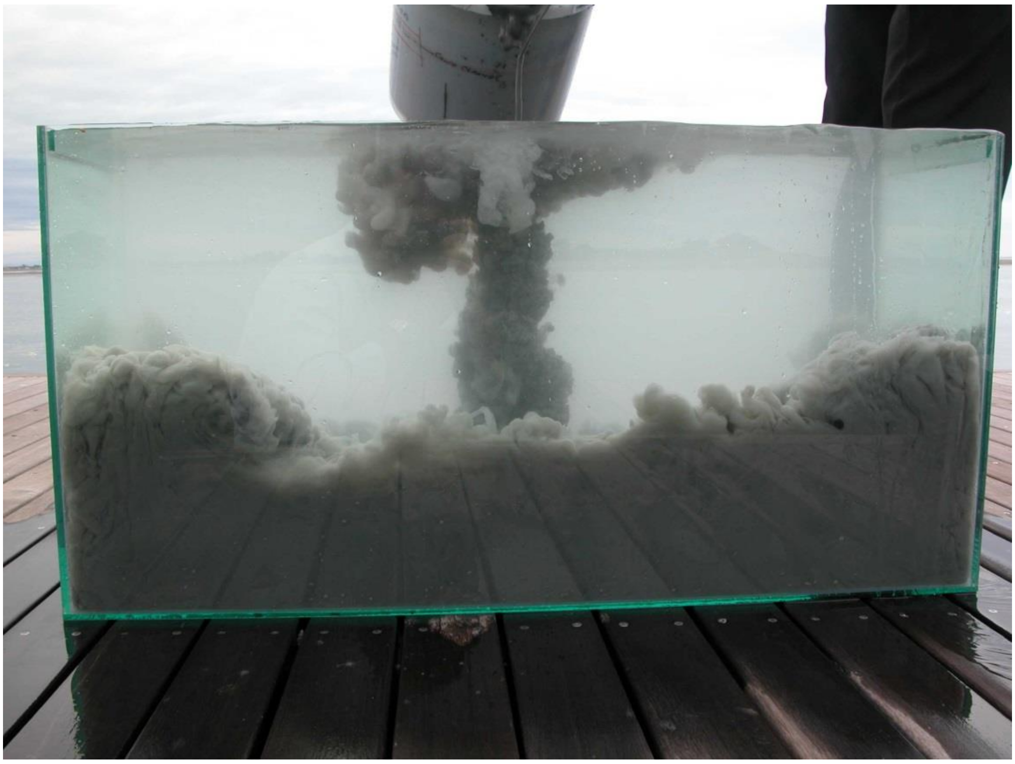
Photograph No 15

2. The hopper contents are released in a very short period of time and the material is released as a liquid slug into the receiving water overlying the dumping area. The specific gravity of the fluid dredged material is 1.3. The output from the dredge pump is discharged overboard until the specific gravity of the fluid reaches 1.3 at which point the discharge is directed into the hopper.

3. The dense fluid sinks down through the seawater in a three step process: convective descent during which the material falls under the influence of gravity; dynamic collapse when the descending cloud impacts the bottom, transforming into the third stage horizontal outflow from the impact point.

4. The outflow disperses radially outwards until passive transport dispersion commences when the material transport and spreading are determined more by ambient currents and turbulence than by the dynamics of the disposal operation.

5. To gain a better intuitive understanding of the process a sample of the dredged material recovered from the dredge pump discharge pipe into the hopper of the Pelican was tipped into a seawater filled fish aquarium tank. The result is shown in Photograph No 16.



Photograph No 16

6. The dredged material suspension forms a jet through the receiving fluid, strikes the seabed and spreads out horizontally underneath the seawater. In the photograph the dredged sediment suspension is shown colliding with the ends of the tank and reflecting back. In the real case no such restraint exists and the fluid continues to spread radially out from the discharge point. Of note is the clear separation between the two fluids until the turbulence produced by reflection off the ends of the tank produces mixing of the two.

7. The Coastal Engineering Research Centre (CERC) has developed a computer program Short Term Fate (STFATE) which can be used to model the descent and dispersion process. STFATE is a deterministic, sediment fate numerical model for predicting the short term behaviour of dredged material dumped in open water. This program was used as part of the LPC study and the results of the STFATE modelling are included in Section 7.6.

8. MSL have independently modelled the dispersion of sediment from the dump location, short term and long term dispersion, using a sophisticated numerical model. The short term footprint replicates the STFATE model results.

9. The nature of the dumped sediment will be different for the maintenance and CDP operations. The channel infill material removed by the maintenance dredge is close to fluid to start with, the amount of consolidation will be low. Once entrained by the dredging process it will be a closer representation of a dense fluid than the virgin material entrained by the capital dredge. The CDP material in contrast has cohesion and structure and small lumps or chips will stay together during the passage through the dredge pump.

10. The practical consequence of this is that more material is likely to initially stay close to the dump point and the turbidity will be less for the CDP material. The chips will rapidly drop out of the density flow. While the chips will still be moved by swell action the capital dredged material will as a whole consolidate

faster and become a relatively permanent part of the seabed faster than the material dumped from the maintenance dredge.

11. While the MSL model does not handle 'chips' – the proportion and size of which is indeterminate prior to the engagement of a dredge – the MSL results effectively provide a conservative upper limit for the movement/mobility of the sediment from the dump site. The MSL model is the best available model for the long term distribution of the sediment from the dump site.

6.2 Practical Dump Trials

1. The contract maintenance TSHB Pelican has been used on three separate occasions to undertake practical test dump trials of hopper/loads dredged material during maintenance dredging campaigns. Test dump trials have been undertaken at Gollans Bay within the harbour, at Godley Head and the proposed offshore dump location. The first trial at Gollans Bay was undertaken in 2003 and the offshore dump trial was in 2007.

2. For each trial the dispersion of a hopper load of the dredged material dumped by the Pelican was investigated at full scale using an ADCP instrument deployed from the OCEL survey boat shadowing the Pelican as it moved to empty its hopper. The survey work was undertaken in calm seastate conditions, swell wave height 0.5 m.

3. The back scatter measurement technique was used to measure the suspended sediment transport of dredged material dumped from the Pelica'. An RDI 1200 kHz Workhorse Monitor ADCP was used to measure suspended sediment in the water column. Positioning was input into the ADCP via a Trimble 5700 RTK GPS. Again this is a qualitative rather than a quantitative measure, it does not give TSS values.

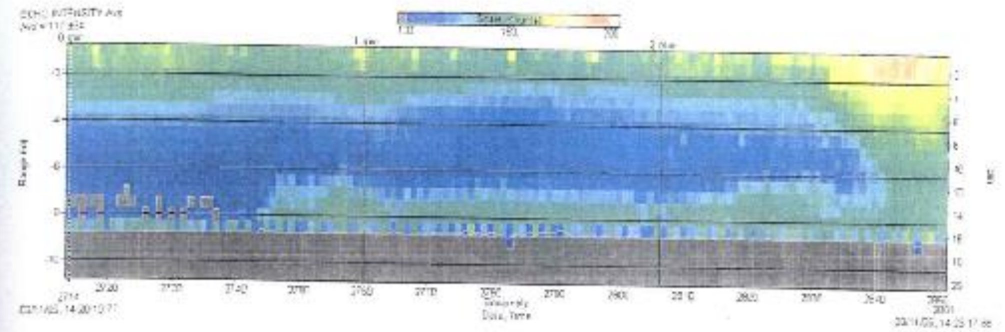
4. A number of ADCP transects through the centre of each dump position were carried out to measure relative suspended sediment through the water column. The ADCP data was processed and output to an ARCVIEW GIS application that converted the data into a GIS format.

5. The initial transects into the sediment plume for all of the dumped dredge hopper loads proved unsuccessful as the acoustic signal of the ADCP could not penetrate the extremely high initial suspended sediment concentrations near the water surface at the drop zone. However as the descending sediment plume hit the seabed it spread away from the initial drop zone enabling the ADCP to measure the advancing front on the seabed. Transects were then conducted towards and away from the advancing seabed flow.

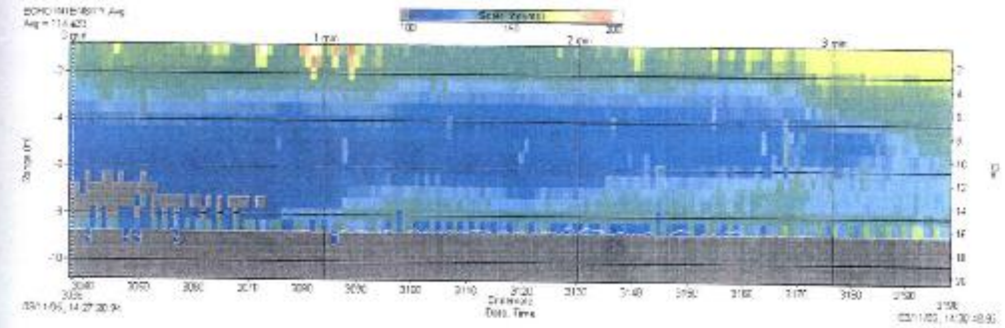
6. The work carried out in 2003 inside the harbour gave quite clear results from the echo intensity plots the principal two features of which, Figure No 9 shown were:

   - A turbid surface plume of 2 to 3 m thickness away from the drop zone, and
   - A bottom layer of suspended sediment visible approximately .25 to 1.5 m above the seabed.

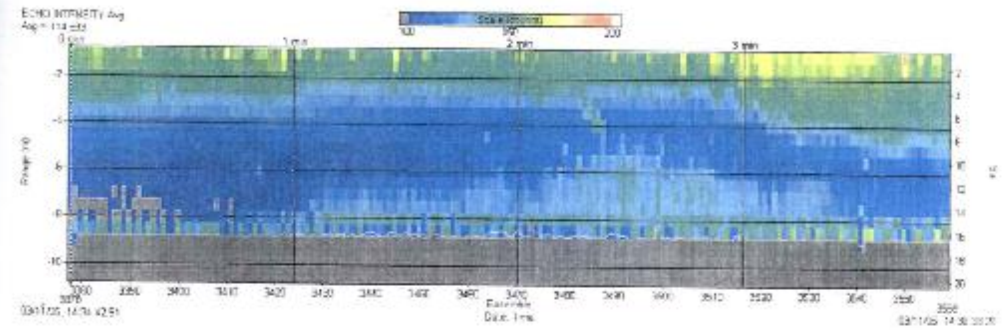
   This is the same pattern as shown in the aquarium representation of the process, see Photograph No 16.



Echo intensity along ADCP transect 6 (drop zone at right of figure, start transect time 14:120, time since release ~16 minutes).



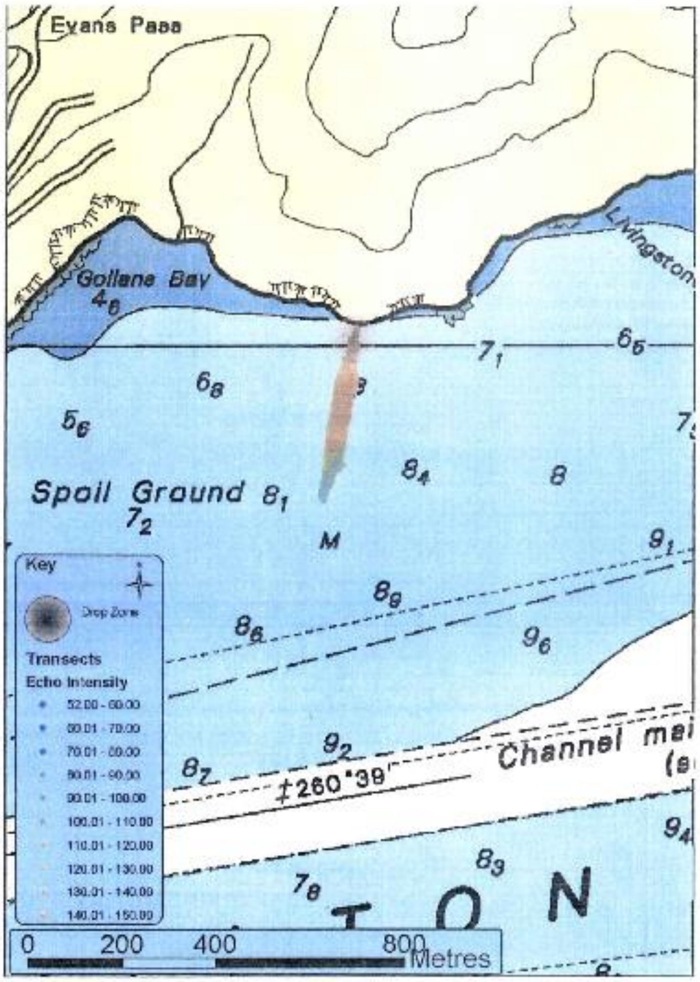
Echo intensity along ADCP transect 8 (drop zone at right of figure, start transect time 14:27, time since release ~23 minutes).



Echo intensity along ADCP transect 10 (drop zone at right of figure, start transect time 14:34, time since release ~30 minutes)

Figure No 9

7. Tracking the leading edge of the plume indicated that the material dumped by the dredge could travel some 300 m from the drop zone in a period of approximately 40 minutes following the time of the dump, see Figure No 10. The volume of material shifting cannot be quantified by the results obtained although it must be noted that the echo sounder traces on the dump location indicated that there was no perceptible reduction in the water depth at the dump location. This in turn indicates that the dumped material was widely dispersed. This confirms the visualisation of the dumping process as a mixing of fluids of differing densities rather than a drop of solid material.



Location diagram of drop zone, ADCP transects and main channel (in white). (Based on NZ Chart 6321, LINZ 2000).

Figure No 10

8. The echo sounder trace did show a transient turbidity plume immediately after the dumping, the same as shown in Photograph No 17 for the proposed offshore dump location.

Photograph No 17

9. The results were not so clear cut in respect of the 2007/2008 work outside of and at the entrance to the harbour. It proved difficult to track the plume produced by the dumping once the plume had started to spread out, and the back scatter levels decreased. This was because of relatively high levels of ambient or natural background turbidity. The plume can only be tracked while the back scatter values are elevated, and higher than the ambient back scatter values otherwise the plume becomes indistinguishable from the natural background. Tracking was also complicated by stratification at the offshore site and small differences in current speed and direction through the water layers.

10. At the offshore dump location the plume cloud moved south east, roughly parallel to the line of the coast, consistent with an ebbing tide. As for the in harbour work the surface plume was much smaller than the plume at depth. At depth a plume footprint approximately 200 m wide was observed before it became indistinguishable from the natural background. An absolute plume extent at depth could not be estimated.

11. At the Godley Head location the dump took place close to low water. Water current profiles indicated that at this time the current direction was generally north north east, water leaving the harbour , in the upper portion of the water column but south to south west at depth, indicating denser water entering the harbour. The natural background turbidity was higher in the Godley Head area than offshore most likely as a consequence of the outgoing tide carrying more turbid water out of the harbour. The extent of the plume at depth before it became indistinguishable from the natural background was 150-200 m.

12. The turbid plume produced by the dumping adds to the natural background turbidity and becomes indistinguishable from it but is reflected in a resulting turbidity spike.

13. The speed of sedimentation or dropout of the sediment particles from the turbidity plume, is related to the concentration of the solid particles in the fluid. The setting rate u can be expressed as $u = u(c)$ where $u(c)$ is a function of the particle concentration in the suspension fluid.

14. The higher the concentration or saturation of the water column with suspended solids the faster the sediment will settle out. With increasing interparticle collisions as a consequence of the higher concentration of particles the probability of formation of flocs from dispersed (nonfloculated) particles increases.

15. For any given level of wave disturbance of the seabed there will be an associated natural background or equilibrium level of turbidity. A sudden addition in the form of a plume of dumped dredged material will be a transient spike with no lasting enhancement of the natural background level.

16. Until the dumped material consolidates to become closer to the natural seabed at the dump location the natural turbidity levels in the immediate area will be higher than was originally the case because the same level of wave action will entrain more of the unconsolidated material.

6.3 Susceptibility to Entrainment by Wave or Current Action

1. The fine sediment, predominantly silt sized sediment characteristic both of the harbour seabed and the mobile fluid layer in Pegasus Bay, is susceptible to disturbance by wave or current action, either in its natural undisturbed state or even more so in its as dumped, unconsolidated state.

2. The most important hydrodynamic property of waves and currents for sediment transport/disturbance purposes is the bed shear stress they produce. The bed shear stress is a function of the square of the water particle velocity irrespective of whether the water particle velocity results from wave or current action. When the shear stress exceeds a critical value movement initiates.

3. For a smooth seabed and relatively small wave particle velocities the boundary layer may be laminar, but more often in cases where sediment is in motion it will be turbulent. The boundary layer - in which the water particle velocity rapidly decreases to zero at bed level - is only a few millimetres or centimetres thick for waves but can be of the order of metres thick for steady currents.

4. This has the effect of producing a much larger velocity shear in the wave boundary layer which in turn causes the bed shear stress produced by a wave with orbital velocity U_w to be much larger than the bed shear stress developed by a steady current U_c of equal speed. Waves are more effective in stirring the seabed than currents.

5. The critical shear concept for unidirectional flow is based on the Shields criterion (Shields 1936). The criterion expresses the critical value of the ratio of the destabilising fluid forces to the stabilising forces that act on the particle. The forces that tend to move the particle are related to the maximum shear stress exerted on the bed by the moving fluid, so the stabilising forces are related to the submerged weight of the particle.

6. When the ratio of the two forces represented by the Shields parameter, ψ, exceeds a critical value, $\psi_{c,}$ movement initiates. The shield criterion (for steady flow) is:

$$\psi_c = \tau_c / \{(\rho_s - \rho_c)\cdot g\cdot d\} = u_{cr}^2 / (\Delta\cdot g\cdot d) = f(R_e)$$

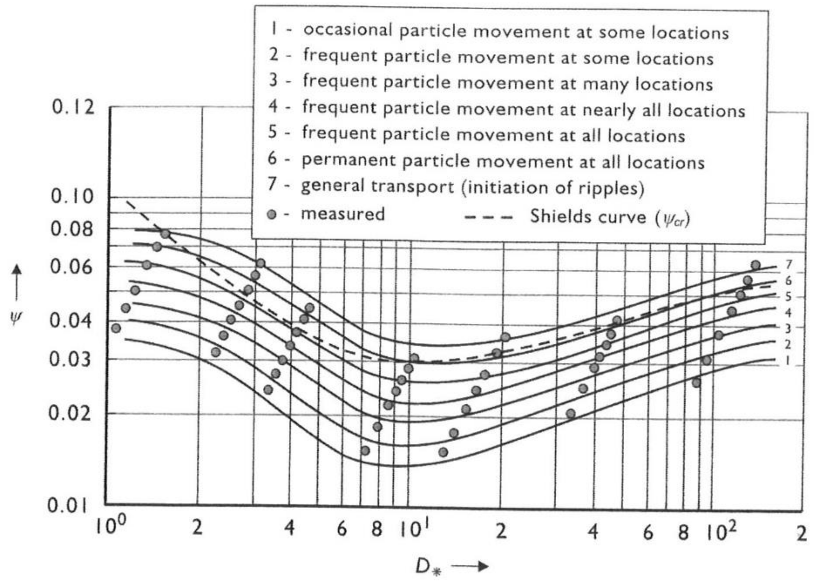
Where:

τ_c = critical value of bed shear stress induced by the fluid at particles first begin to move (N/m^2)
ρ_s = apparent mass density of particles (kg/m^3)
ρ_w = mass density of seawater (kg/m^3)
d = particle size, median d_{50} often taken as characteristic value
$D^* = d_{50}\cdot(g\cdot\Delta/ v^2)^{1/3}$ non dimensional grain size
u_{cr} = critical value of shear velocity (m/sec)
$R_e = u_{cr}\cdot d/v$ Reynolds no. based on shear velocity
Δ = relative buoyant density of the particles
v = kinematic fluid viscosity (m^2/sec).

7. The Shields diagram which establishes a relationship between the critical Shields parameter and the shear Reynolds number is the most widely used criterion for incipient motion of sediment. The difficulty is the implicit nature of the criterion, u_{cr*} appears on both axes of the diagram and for a specific set of fluid and sediment data an iterative process is required to find the critical bed shear stress.

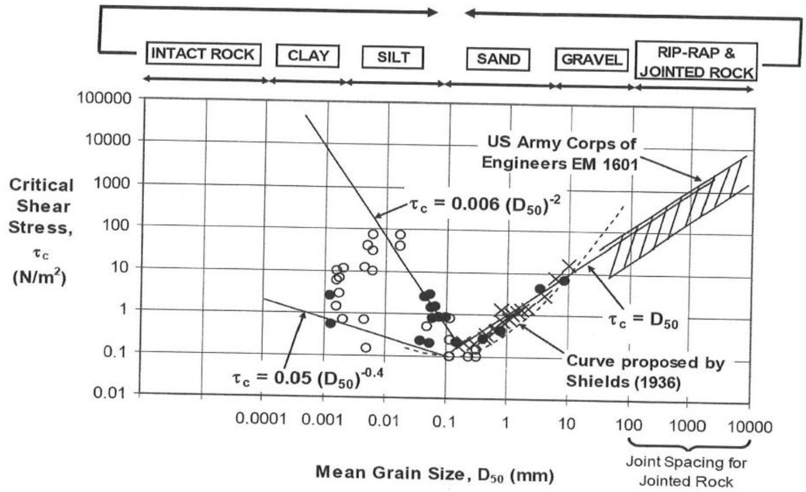
8. A modified Shields diagram (CIRA, CUR, CET MEF 2007) for steady flow is shown in Figure No 11. The critical Shields parameter can be determined directly from the fluid and sediment characteristics. Figure No 12 presents a plot of critical shear stress as a function of mean grain size of particles. This shows that the most erodible material is fine sand and also shows that for fine materials – silt and clay – with cohesion the erosion threshold does not correlate with mean particle size.

9. Based on the lower line $\tau_c = 0.5\ (d_{50})^{-0.4}$ the critical shear stress for steady flow is 0.2 N/m^2 for silt d_{50} = 0.03 mm (30 µm). This is in the range for weakly consolidated mud (silt-clay less than d = .062 (62 µm) (Van Rijn 2007a) MSL used the 0.2 N/m^2 critical shear stress value for the sediment dynamics modelling. This is for steady flow conditions wave induced flows will be turbulent and the critical stress to initiate movement correspondingly less.



The modified Shields diagram for steady flow (CIRIA; CUR; CETMEF, 2007)

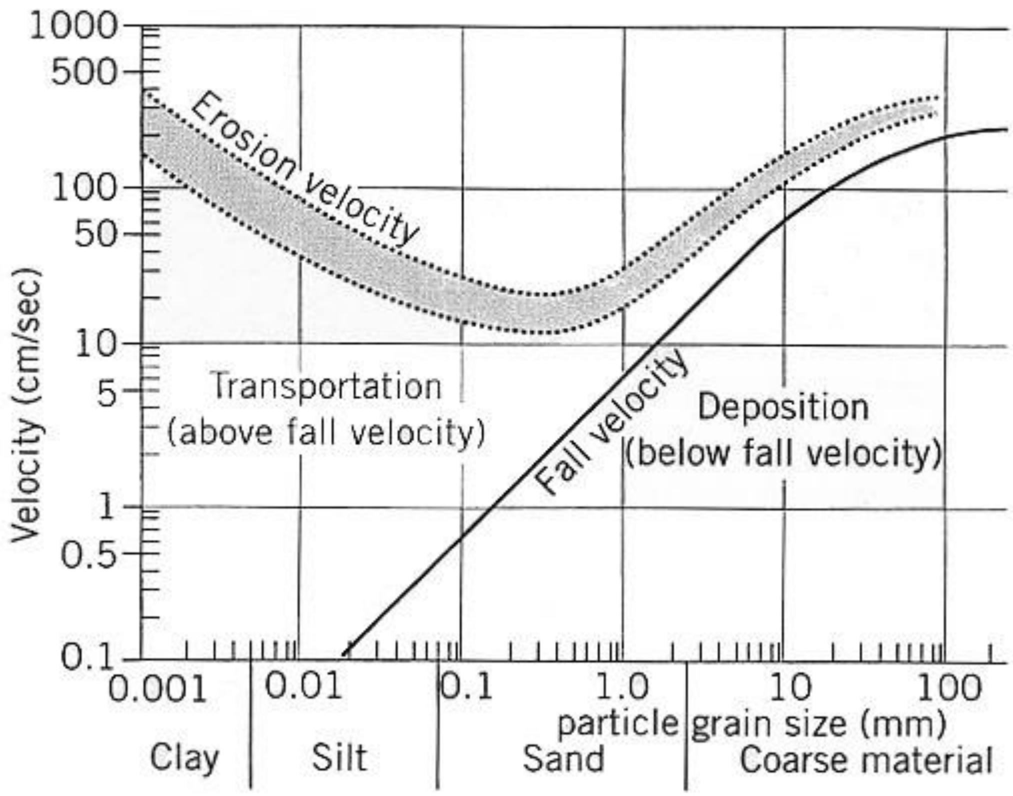
Figure No 11



Critical shear stress vs grain size (Briaud et al, 2001)

Figure No 12

10. The Hjulstrom diagram, Figure No 13, is an earlier much more simplistic representation of the process of sediment entrainment, based on the critical velocity concept, for steady state currents but it has value because it gives the order of magnitude for the current speed required to suspend fine sediment. It is in excess of the value to initiate movement based on the Shields criterion so can be taken to represent the velocity eroding the sediment and entraining it into suspension.



Hjulström Curve

Figure No 13

According to the critical velocity concept, initiation of motion of sediment occurs when the critical or permissible velocity is exceeded.

11. The entrainment of fine sediment is a complex process. The silt particles are so small that electrochemical force and viscosity become significant. The current speed required to erode consolidated silt and clay material is higher than for fine sand because of the cohesion exhibited by the fine particles and the smoothness of the seabed. The erosion velocity for silt is of the order of .3 m/sec bearing in mind the greater effectiveness of waves relative to steady currents in disturbing the seabed.

12. If the sediment is unconsolidated as in the case of dumped dredged material (same for CDP and maintenance) then the velocity thresh hold for movement is lower. Once in suspension the velocity required to keep it there is lower than the erosion velocity - as indicated on the diagram.

13. The dumped dredged material is primarily in the form of a slurry or dense fluid with chips of stiffer cohesive material entrained in it for the CDP material. The slurry or fluid mud transforms slowly into a soil through a process of consolidation under self weight. Self weight consolidation starts at the bottom of the deposit while sedimentation continues at the top.

14. During the process of transformation from a fluid mud into soil the shear strength of the dumped material increases and as it is increases the susceptibility of the material to entrainment by wave action decreases to approach that of the undisturbed soil.

15. The mud is defined as a sediment-water mixture which consists of particles that are predominantly less than 63 µm in size, exhibits viscoelastic rheological behaviour when the mixture is particle-supported, and is highly viscous and non-Newtonian when it is in a fluid like state.

16. The viscosity is dependent on the solids volume fraction φ (or porosity $\eta = 1 - \varphi$) and interparticle interaction I. At low values of φ the viscosity increases slowly with increases in φ but tends to increase rapidly when particle packing becomes dense. For randomly packed spheres this change occurs at about $\varphi = 0.60$.

17. A simple viscoplastic model is the Herschel-Buckley, equation $\tau = \tau_y + K\gamma^n$ where τ_y is the yield stress γ is the flow shear (strain) rate, K and n are the constants for a given sediment and n = 1. For fluid muds n typically ranges from 0.3 to 0.9.

18. When n = 1 the equation describes the Bingham model $\tau = \tau_B + \eta m\gamma$, in which the (Bingham) yield stress $\tau_y = \tau_B$ is equal to the threshold stress at and below which the material is a solid, and above which behaves as a Newtonian fluid.

19. During wave action the rheological state of soft mud almost always changes. This change is dependent on the relative magnitudes of the applied shear stress τ, the shear strength with respect to erosion (or critical shear stress) τ_s and the plastic yield stress τ_y (or the Bingham yield stress τ_B). Three change in bed state cases are considered by Jain and Mehta, Handbook of Ocean and Coastal Engineering.

20. $\tau \leq \tau_s < \tau_y$ wave action is too weak to erode the bed surface. However wave orbits can penetrate the bed and build up excess pore pressure breaking interparticle bonds. Mud rigidity decreased even as particle packing density may remain largely unaffected. The seabed changes to a fluid like transitory state which reverts to bed as soon as wave action ceases and interparticle bonds are re-established.

21. $\tau_s < \tau < \tau_y$. The bed is subject to pressure work and shear work with the result that pore pressure build up eventually destabilises the particle matrix. The bed is liquefied and its surface erodes causing the water to become turbid. There may be no significant change in bed density. Fluid like mud reverts to bed when wave action ceases.

22. $\tau_s < \tau_y < \tau$. The bed yields rapidly, erodes significantly and water becomes highly turbid. When wave action ceases fluid mud develops which is initially significantly lower in density than the original bed. In due course thixotropic gelling and bed consolidation cause the density to increase to its original value.

23. A prime factor in the transport and fate of fine sediment is the exchange of fine sediment between the seabed and the water column above. In the Delft 3D morphological model used by MSL the sediment flux between the water phase and the seabed is calculated using the Partheniacles-Knone formulations. The erosion flux E (kg/m^2/sec) $E = M (\tau_{cw} - \tau_{cr}) / \tau_{cr}$ for $\tau_{cw} > \tau_{cr}$.

Where M is a user defined erosion parameter kg/m^2/sec

τ_{cw} is the maximum bed shear stress due to current and waves
τ_{cr} is the user defined critical erosion shear stress N/m^2 (0.2).

24. The deposition flux D (kg/m^2/sec)

$D = W_s.C_b.(\tau_{cw} - \tau_{cd}) / \tau_{crd}$

Where W_s if the sediment settling velocity (m/sec)
C_b is the average sediment concentration near seabed (kg/m^3)
τ_{crd} is the user defined critical deposition shear stress N/m^2).

The erosion and deposition formulae have been used in mathematical models in part because of their simplicity. A key parameter is the user defined erosion parameter M.

25. MSL have done sensitivity testing of the erosion parameter and show the effect of changing M on the predicted bed level changes in Figure 3.1 of the MSL report Numerical Modelling of Sediment Dynamics

for a Proposed Offshore Disposal Ground Rev F. Effectively the erosion parameter scales the predicted bed level changes approximately linearly.

26. MSL note that while the general patterns of erosion accretion predicted are likely to be accurate, without calibration or validation of the model using measured data the results can only be assessed based on anecdotal evidence. This suggest that an M value of 1×10^{-6} represents what is seen within the environs. The erosion parameter can be tuned to match measured data when it is available.

27. MSL are confident that they now have a good indication on the magnitude of the erosion parameter M. The general patterns of erosion and deposition emerging are consistent regardless of the chosen M value, it is just the magnitude of change which changes and MSL are currently working towards a full validation of the morphological model.

7.0 TURBIDITY

1. Turbidity is a description of the clarity of water, how clear it is. In simple terms it is a measure of the water's cloudiness. This cloudiness results from the intense scattering of light by fine particles suspended in the water. In more precise terms turbidity is an expression of the optical properties of water that causes light to be scattered and absorbed in the water. Turbidity changes the direction of the light rather than letting it be transmitted through the water in a straight line down to the seabed.

2. The attenuation of light due to scattering and absorption as rays of light pass through the water reduces visual range in water and light availability for photosynthesis. Scattering of the light by the suspended particles illuminates the particles, much like a ray of sunlight illuminates specks of dust in the air.

3. The clarity and colour of water are manifestations of the behaviour of light in this optical medium. Essentially all important aspects of the clarity and colour of water can be explained in terms of the light absorbing and light scattering properties of water. These are inherent optical properties of the water and its suspended sediment. The distinctive, characteristic aquamarine colour of the water in Lyttelton Harbour results from the fine sediment - silt and clay size – particles suspended in the water.

4. Colour depends on the light scattered back to the observer. Brightness depends on the amount of scattered light. Hue depends on the wavelength of the scattered light which is determined primarily by selectivity of light absorption. Clay size suspended particles scatter light most efficiently.

5. Turbidity is a natural background phenomenon that occurs in most bodies of water. The waters of Lyttelton Harbour are naturally turbid the waters of Pegasus Bay less so most of the time. The turbidity of the harbour water and Pegasus Bay water fluctuates in response to natural processes, being increased by rain events, and swell waves that stir up the seabed sediment. When calm returns turbidity levels decrease.

6. The mussels on long lines in Port Levy thrive despite the turbidity and the shells are coated by sediment settling on the mussel shells – reference Photograph No 18. Divers working in the harbour have to be fee of claustrophobic tendencies to be able to cope with the black water conditions that prevail in the harbour. Typically below 5 to 10 m, dependent on swell conditions, all light is gone, total blackness.

Photograph No 18

7. The discharge from the Waimakariri River into Pegasus Bay north of Christchurch produces a major plume when the river is in flood as a result of heavy rain in the mountains in north west wind conditions. This plume typically spreads south along the Christchurch coastline to the Lyttelton Harbour entrance. Photograph No 19 shows the leading edge of a turbidity plume from the Waimakariri River in flood close to Godley Head. The outgoing tidal flow from Lyttelton Harbour, shearing off post Godley Head, provides a clear defined dividing line and has stalled plume progress further south

Photograph No 19

8. The plume from the Waimakariri is typically not that visually significant when viewed from the Pegasus Bay beaches. A person standing on the beach is likely to be able to see about 5 km out to sea and the presence of the plume is not that discernible given that the observer is looking obliquely at the sea surface and mainly sees reflected sunlight and waves. If that observer is in the water he/she will feel the presence of the plume, the fresh water is colder than the sea water.

9. A person on the cliffs at Scarborough – the location of Photograph No 19 – can clearly see the plume. Looking either straight down or at a relatively steep angle to the water an observer sees almost entirely water leaving radiance in calm conditions. Photograph No 20 shows a view of turbid water plume extending out from the Christchurch estuary, taken from Clifton Hill. In the background, left, out to sea, the discharge from the Christchurch ocean outfall diffuser is apparent.

Photograph No 20

10. The coastal waters of Pegasus Bay and Lyttelton Harbour exhibit high natural variability in their characteristic properties. There are substantial variations in the turbidity from day to day, variations generally directly attributable to natural causes - high energy seastate events, rainfall events and river flood discharges. It is difficult to establish characteristic background levels other than to note high natural variability. The key point is that this variability is natural and any turbidity introduced by the proposed dredging operation will not produce an isolated spike in constant background turbidity levels totally at variance with what occurs as a natural process. It will not be a case of a spike appearing against unchanging background levels, but a possible spike difficult to discern from the natural spike variation. Given the ability however to attribute spikes in turbidity levels to natural events it should be possible to pick up the effect of dredging provided the effects are not submerged or camouflaged by a natural event.

11. The particles that contribute to light attenuation in the water must stay suspended for a reasonable length of time and are therefore slow settling. Coarse particles drop out quickly once the source of the sediment disturbance, typically wave action, drops below the entrainment initiation level. Fine particles may only drop out when complete calm returns.

The settling velocity of fine particles v_s, is given by Stokes' law:

$$v_s = \alpha.g.d^2(\rho_s - \rho)/ 18\eta$$

Where α is a dimensionless shape factor, g is the gravitational acceleration, d is a characteristic linear dimension (diameter for a sphere), ρ_s is the density of the particle, ρ is the density of water and η is the absolute viscosity of water. The equation shows that the settling velocity is mainly dependent on the particle size and density relative to water although shape – deviation from sphericity as indicated by α – also has an effect.

12. Mineral particles typically have densities similar to or greater than quartz, $\rho_s = 2.65$, and generally only remain in uniform suspension if particle diameters are smaller than the sand-silt boundary at 50 µm. This is the case for the bulk of the Lyttelton Harbour sediment. The settling velocities for silt sized material, 2 – 50 µm diameter range from 3 µm/sec < vs < 2 mm/sec. A particle at the clay–silt boundary settling at around 3 µm/sec takes about 4 days to settle 1 m in perfectly calm water. It takes very little turbulence to maintain the fine sediment in suspension. This is for isolated widely dispersed particles not for turbid suspensions. The settling rate is related to the concentration of solid particles in the fluid – with increasing interparticle collisions as a result of higher concentration flocs develop.

13. The settling velocity of sediment particles in the fine silt/clay range <40 µm is primarily influenced by the proximity of similar size particles, ionic forces and the consequent tendency of the particle to aggregate to form flocs. Flocs can be an agglomeration of thousands or more mineral particles. In the absence of in situ measurements on the settling velocity of flocs of cohesive material in Lyttelton Harbour assumptions have to be made to resolve the complexity to derive a settling velocity for use in numerical models. MSL settled on a settling rate of 1 mm/sec for flocculated particles (<4 µm) following the review by H R Wallingford of MSL's original report on the Simulation of Dredge Plumes.

14. The natural condition for the harbour, exposed as it is to swell wave action, is to have fine sediment in close to permanent suspension. A range of factors but principally swell wave action increases the volume of material in suspension (turbidity) during an event and the particles are distributed right through the water column. As the turbulence decreases following the event there is a strong selection towards removal from the water column of the coarser silt ranges because v_s depends on the square of d in the Stokes' law equation but the finer sizes remain in suspension.

7.1 ECan Turbidity Measurements

1. Water sampling, either from vessels, helicopters or moorings has limited ability to assess or monitor large scale natural patterns, ECan has endeavoured to use satellite images of water colour in Lyttelton Harbour to assess the spatial and temporal patterns in turbidity, expressed in terms of the total suspended solids (TSS) content (grams/m^3), in the harbour. TSS is the same thing as Suspended Solids Concentration (SSC).

2. Obtaining useful measurements of TSS from remote sensing methods is not simple, complicated by the fact that satellite data is not available under cloudy conditions. The majority of the NZ coastal zone is obscured by cloud on most days. The lack of measurements on cloudy days introduces a bias – the TSS values on cloudy days are more likely to be elevated, TSS is higher after rainfall events.

3. The ECan work on remote sensing by satellite of turbidity has contributed to the understanding of turbidity in Lyttelton Harbour obtaining useful measurements of TSS which correlate well with ECan's existing extensive database on in situ measurements. The ECan results showed no clear seasonal pattern. Storm flow inputs and resuspension in high energy seastate events dominated over expected seasonality in sediment inflow from land sources. The main findings from the analysis of the satellite data was that long term median concentrations of TSS in the upper Lyttelton Harbour were estimated as 21 g/m^3 decreasing to 9.3 g/m^3 near the Heads.

4. These findings of higher turbidity (TSS) in the upper harbour accords well with OCEL measurements reported in the following section. The OCEL measurements also fit the ECan database results.

7.2 OCEL Turbidity Measurements

1. Turbidity can be measured using a nephelometer which is a meter that measures the intensity of light scattered at 90˚ to a beam of light – optical back-scatterance (OBS). It is based on a photoelectric detector that is very sensitive to changes in attenuated light. Measurement of the optical properties of suspended sediment is more relevant in many instances than the measurement of its actual mass concentration given that much of the impact of suspended sediments relates to its light attenuation which reduces visibility and photosynthesis.

2. OCEL's turbidity sensor measures turbidity in FTU's or Formazine Turbidity Units, an expression of the optical properties of water that cause light to be scattered or absorbed and is directly related to turbidity. The other common unit for the measurement of turbidity is the NTU or Nephelometric Turbidity Unit. The FTU and NTU numbers are close to equivalent – FTU for OBS based on 180° scatterance and NTU for OBS based on 90° scatterance.

3. Nephelometric turbidity, an index of light scattering by suspended particles, has been widely used as a simple, instrumental surrogate for suspended sediment it is however only a relative measure of scattering that has no intrinsic environmental relevance until correlated against a proper scientific quantity such as a direct measure of the total suspended solids (TSS) concentration in milligrams per litre.

4. The turbidity readings. In FTU or NTU units, can however be correlated with TSS values and this has been done by CRL Energy Limited for a number of different samples, taken by OCEL at varying depths and locations in Lyttelton Harbour. This correlation is reported on in Section 7.3.

5. Turbidity in the harbour varies both spatially, and vertically with depth, in the harbour, dependent principally on weather and seastate conditions and vessel movements. Propeller wash from large vessels moving in and out of the port along the navigation channel stirs up the seabed putting sediment into suspension.

   Turbidity plumes on the sea surface resulting from vessel movements and dredging are transient and soon fade away by merging with the background turbidity.

6. OCEL has undertaken turbidity measurements in Lyttelton Harbour using a nephelometer on three separate campaigns, 2003, 2008 and 2015.

   The OBS turbidity sensor was deployed from the OCEL survey boat at a number of locations around the harbour as part of these campaigns to investigate turbidity levels and the variation of turbidity with depth under a range of conditions. Plumes resulting from vessel movements were also investigated. The turbidity sensor output is a plot of FTU number versus depth in the water column at the location sampled.

7. The turbidity depth profiles typically show a hockey stick profile, the turbidity increasing close to the seabed. This is a natural condition as a consequence of the greater density of the water containing suspended sediment relative to water with no suspended sediment. The denser fluid gravitates to the seabed where it forms a layer. The suspended sediment gradually transforms from a fluid to a soft fluid mud which, as it consolidates, develops cohesion. The NIMROD dynamic penetrometer device was used to investigate the fluid mud layer. The results are reported in Section 11.

8. The hockey stick profile is also a reflection of the fact that in other than high seastate events the low tidal current speeds and low wave induced particle velocities at seabed level are insufficient to diffuse the bottom layer upwards into the overlying water. In high seastate events turbidity is more evenly spread through the water column.

9. The first deployment of the turbidity sensor was undertaken at the end of the 2003 dredging program while the Pelican was still working in the outer harbour. The dredging operation was found to have no significant effect on turbidity levels in the harbour. The turbidity levels were virtually the same all around the outer harbour.

10. At the time of that survey a south west wind was blowing and the greatest turbidity levels were encountered up in the upper harbour where the locally generated short period waves were stirring up the seabed. A strong southwest wind blowing over the fetch from Governors Bay to the Naval Point reclamation at Lyttelton can generate a steep, short period sea, H_s = 1 m, T_p = 3.5 secs, in the shallow waters of the upper harbour. This can cause the harbour water to become discoloured and highly turbid. A 1m high wave 3.5 sec period in 4 m water depth – off Rapaki – produces a water particle velocity at seabed level U = 0.44 m/sec, in excess of the erosion velocity for silt.

11. A turbidity survey was undertaken on 19 August 2004 following a sustained period of seabed disturbance by swell waves running straight up the harbour. Sampling in the navigation channel, the graphs contained in Appendix C, showed that the turbidity level increased sharply at a depth just above the natural depth to the side of the channel at the point surveyed.

The thickness of the turbidity layer observed in the channel supports the view of the channel as a sediment sink. The pronounced turbidity layer over the natural seabed level to the side of the channel continues across the channel at the same height and the turbidity remains relatively constant through the full depth of the channel trench – see reference Graph C2 Appendix C.

12. Measurements of turbidity made using the OCEL turbidity meter show that the turbidity in the harbour is typically constant or increases only gradually down to 2 m above the seabed after which it increases rapidly. In swell conditions the turbidity is distributed throughout the water column as evidenced by the discoloured water in and outside the harbour. The bottom concentration increases even higher. Examples of the turbidity readings taken on 19 August 2004, displaying the characteristic increase of turbidity in the layer close to the seabed are included in Appendix C. A representative example is shown in Figure No 14.

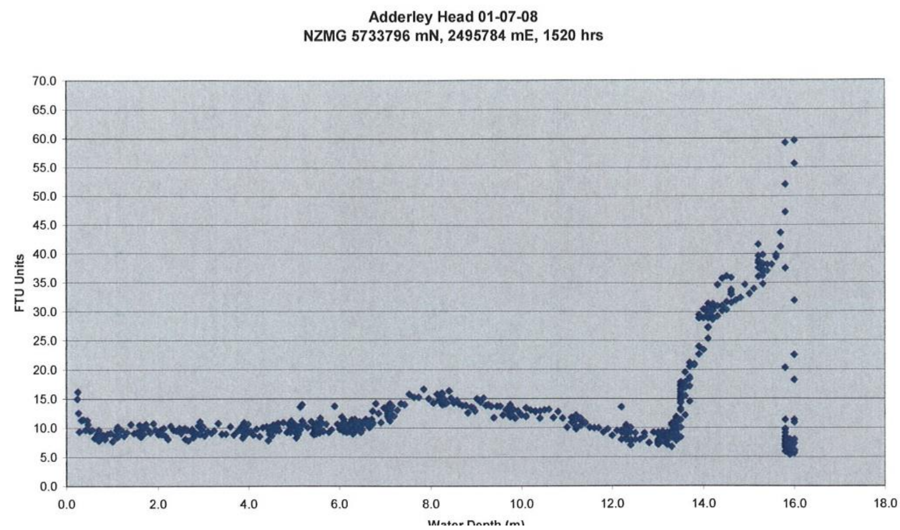


Figure No 14

13. A number of locations around the harbour and Port Levy were tested on 1 July 2008 following a heavy rain event from the south west. The plots are included in Appendix C. The seastate was characterised by less than 1 m swell. The highest turbidity level recorded was in the navigation channel following the arrival of an incoming container vessel attended by a tug. The sea water was strongly discoloured by the

sediment plumes stirred up by propeller wash. At Godley Head, Adderley Head, the entrance to Port Levy, in Port Levy and at Rapaki the turbidity levels were elevated but similar. At Gollans Bay the turbidity level was higher but this may have been related to ship traffic in the navigation channel raising plumes that drifted into the Gollans Bay area. The natural background levels of turbidity are relatively high and only drop off after sustained calm seastate periods. They are elevated by rain events.

14. The turbidity measurement campaign in 2015 was aimed at establishing some idea of background levels of turbidity in the harbour in order to correlate this with the MSL modelling results. A number of locations ranging from the Upper Harbour to outside the Heads – off Rapaki, Charteris Bay, Diamond Harbour, Parsons Rock Beacon, Godley Head, Adderley Head and offshore Taylors Mistake – were sampled on an intermittent basis.

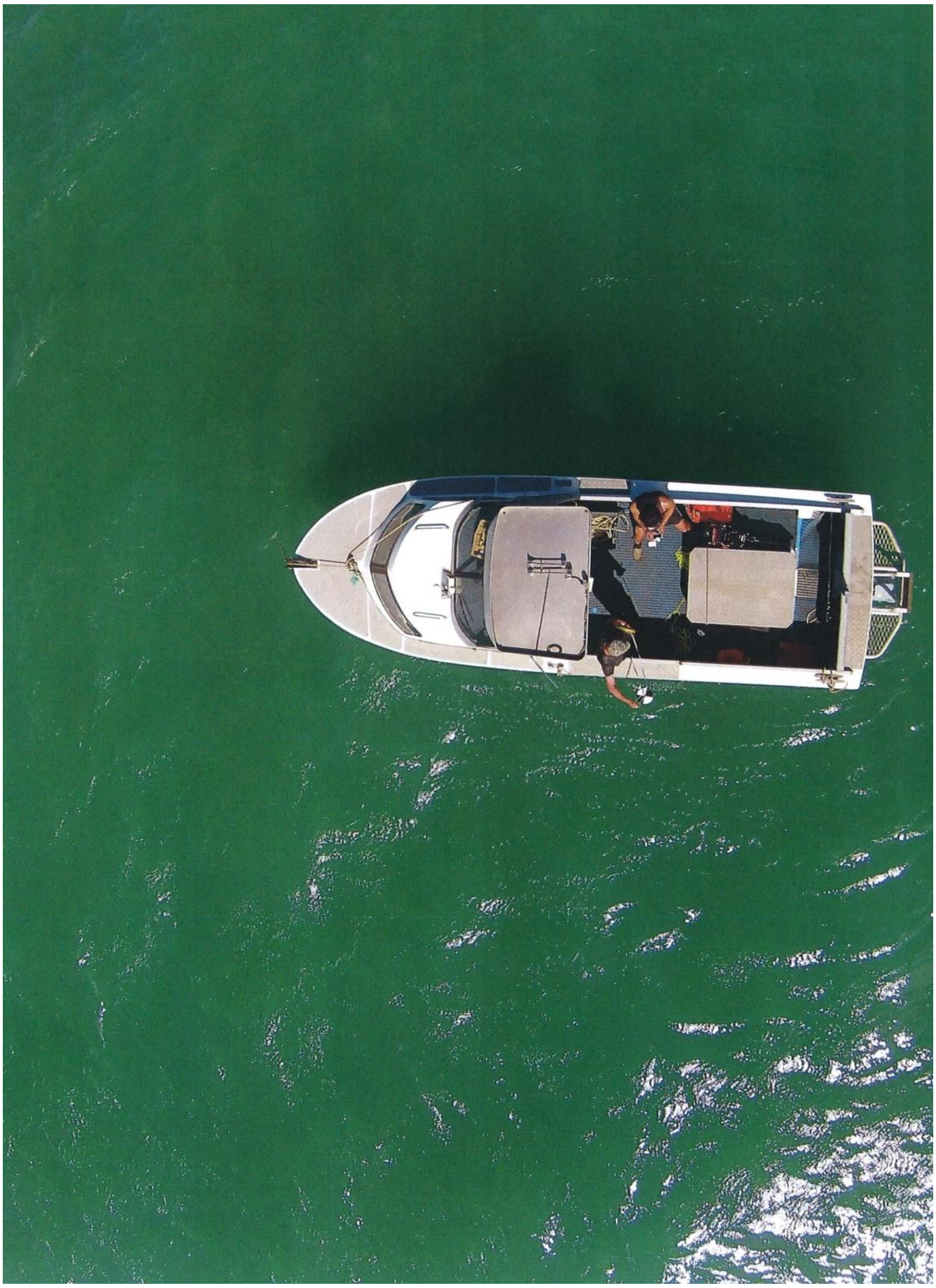
15. Natural variability brought about by episodic events frustrated the ability to establish a consistent natural background other than for the long period of settled fine weather that characterised the summer of 2015/2016. The most turbid water was consistently encountered in the Upper Harbour off Rapaki. The turbidity levels decrease with distance down the harbour towards the Heads. The water off Godley Head was consistently more turbid than water off Adderley Head. The least turbid water was typically found off Taylors Mistake.

16. This is in accord with the ECan remote sensing results and with photographic evidence such as shown in Photograph No 21. That photograph shows the concentration of turbidity on the north side of the harbour for an outgoing tide but can be categorised as an extreme example. The harbour is consistently more turbid on the northern side and more so at Godley Head relative to Adderley Head.

Photograph No 21

17. The prevailing onshore wind in the summer months is the north east wind. This generates short period waves in the harbour fetch that are incapable of disturbing the seabed in the outer harbour but can suspend sediment in the upper harbour when they expend energy on the mud flats in the upper harbour. The suspended sediment is carried by the tide to offshore Rapaki.

18. In addition to sampling the locations using a nephelometer a secchi disk was used to investigate water quality and OCEL's drone was flown to look directly down over the sampling locations to obtain photographs of water colour to correlate with turbidity measurements – Photograph No 22 shows the secchi disk about to be lowered close to Godley Head. The use of the secchi disk to measure visual clarity by measuring the depth, the secchi depth, at which the 200 mm (8") diameter, black and white disk ceases to be visible from the surface, is considered as a better quality than TSS to use for investigating the ecological state of coastal waters. TSS is important for calculating sediment movement in black water. Optical clarity is more ecologically meaningful. The secchi disk figure were found to correlate well with the NTU figures which in turn were found to relate well to the TSS values.



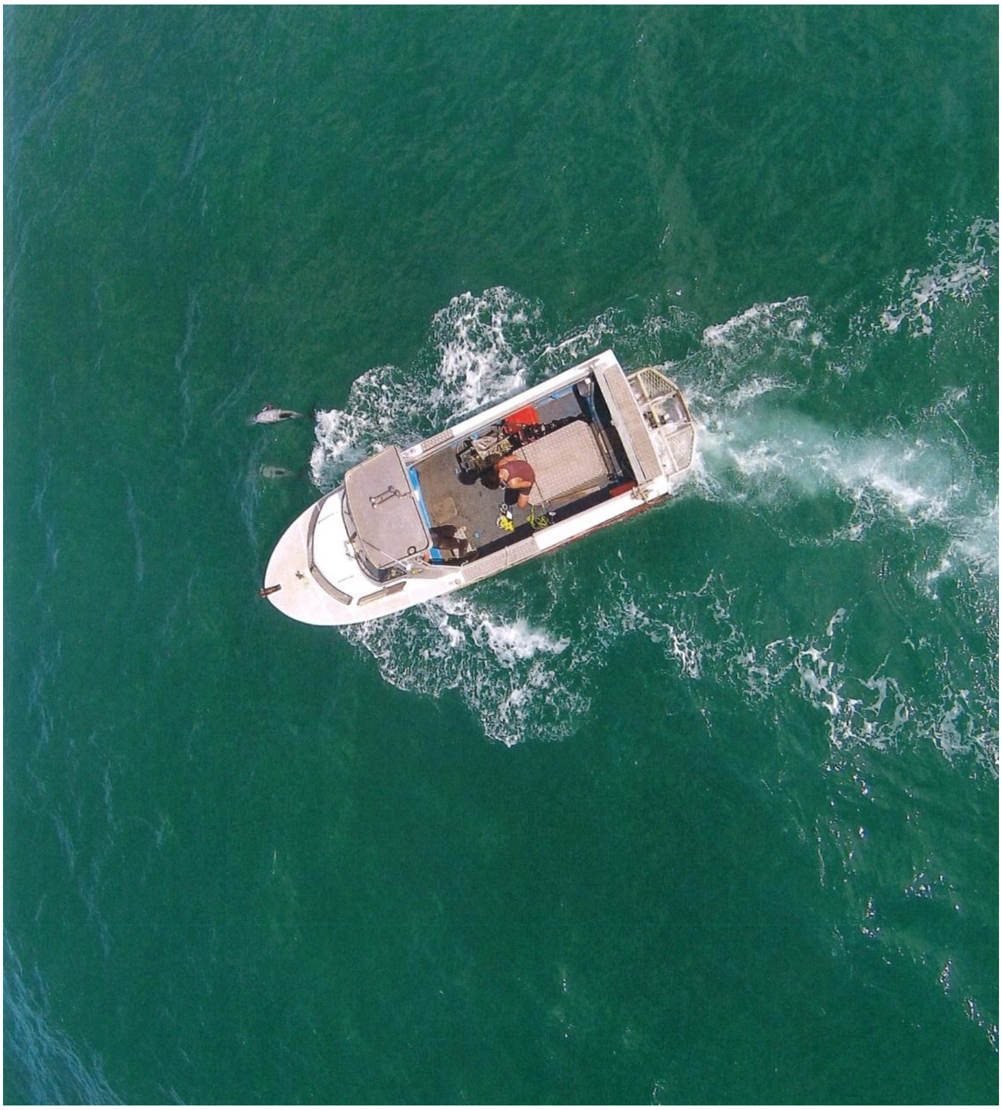
Photograph No 22

19. Typically secchi disk readings for fine north east conditions were

- 0.45 m off Rapaki (NTU 40 close to constant through the 4 m depth)
- 0.8 m at Parsons Rock beacon 18 NTU at surface 30 at seabed
- 0.9 m at Godley Head 18 NTU
- 3.2 m at Taylors Mistake 15 NTU

Photograph No 23 shows three Hectors dolphins in clear – for Lyttelton – water in the outer harbour, approximately secchi disk depth 1 m NTU approximately 20. Photograph No 24 shows two dolphins swimming on the bow wave of the OCEL survey boat in similar conditions. This is about as good as it gets for visibility in the outer harbour.

Photograph No 23



Photograph No 24

7.3 Static ADCP Turbidity Results

1. In addition to its principal use to measure current speed and direction through the water column the ADCP instrument can also be used to track turbid suspensions. By combining acoustic and optical information the ADCP can also provide information about the quantity of particulate matter.

   This information is obtained from the intensity of the received reflection, also referred to as the backscattering strength or signal amplitude. Although no specific suspended solid concentrations can be calculated from the echo intensity alone the echo intensity is an indication of the relative amount of sediment suspended in the water.

2. At the time the offshore dump trial was undertaken using a hopper load of material dredged by the Pelican, there was an ADCP positioned at the offshore dump location primarily to record tidal currents but in a secondary role it monitored turbidity at the location.

   The ADCP record was checked to see if there was an increase in turbidity that could be attributed to the trial dump. There was no effect on the backscatter or inferred turbidity.

3. An ADCP was used to monitor turbidity at the entrance to Port Levy and efforts were made to correlate the turbidity with swell and rainfall events and with periods during which maintenance dredging was undertaken in the harbour. A distinct correlation was established for the rainfall events. Peak turbidity readings correlated with rainfall events. This confirmed earlier work by R M Kirk who suggested there would be such a correlation.

The correlation of turbidity with the rain events is shown in Figure No 15. (Mulgor 2008).

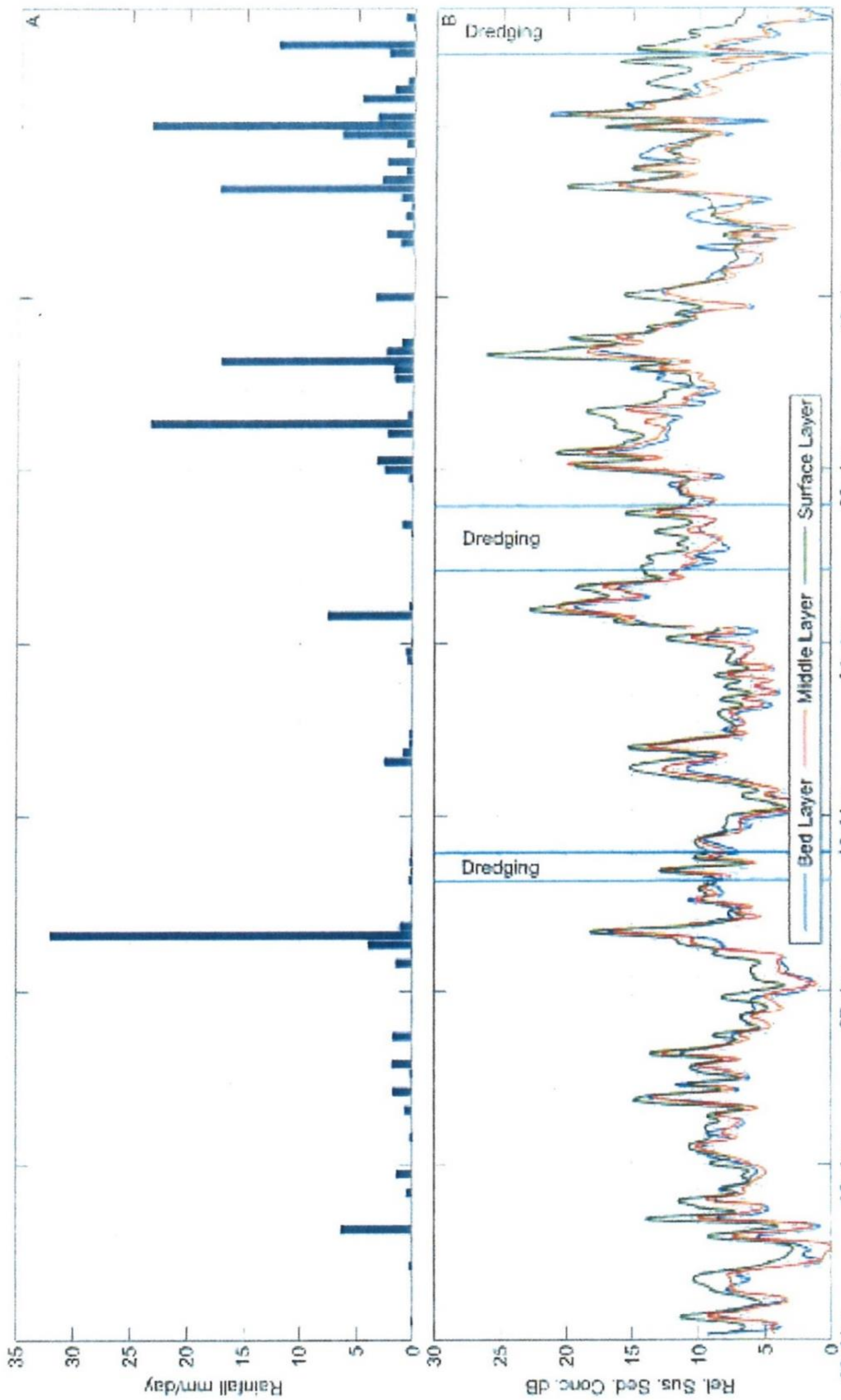


Figure No 15

7.4 TSS FTU Correlation

1. As noted turbidity is a description of how clear water is. In simple terms it is a measurement of the water's cloudiness. It is not a direct measurement of the Total Suspended Solids (TSS) in grams per litre in the water but it is an indication.

2. Turbidity measured in FTUs or NTUs can be translated into milligrams of solid per litre through a correlation based on simultaneously taken water samples. This was done by CRL Energy limited for a number of samples collected from the harbour by OCEL in 2008 and 2015. The TSS correlations and the turbidity meter outputs are given in Appendix D.

3. The highest FTU number 750, was obtained for a sample taken immediately behind the dredge close to the seabed following a dump of a lopper load of dredged material. The TSS value is 935 gm/m^3. Elevated values of the FTU number as high as 750 are transient as the water column becomes saturated with sediment and rapidly drop back as the material drops out of suspension.

   Water sample 6 was taken directly behind the dredge while it was dredging in the channel. The NTU number was 160 corresponding to a TSS of 281 gm/m^3. The turbidity plume – reference Photograph No 5 - behind the dredge is transient and soon fades from view. The turbidity plume disperses in both the horizontal and vertical planes – vertically as the sediment falls to the bottom and horizontally as the plume is broken up by the turbulence in the vortex train wake behind the dredge as it moves.

4. The ECan turbidity data set relating nephelometric turbidity readings to suspended solid concentration (TSS) is shown in Figure No 16. The reduced major axis log-log relationship is

   $$TSS = 3.756\ (NTU)^{0.8668}$$

   The OCEL data gathered in 2008 and 2015 plots close to this straight ling log-log relationship.

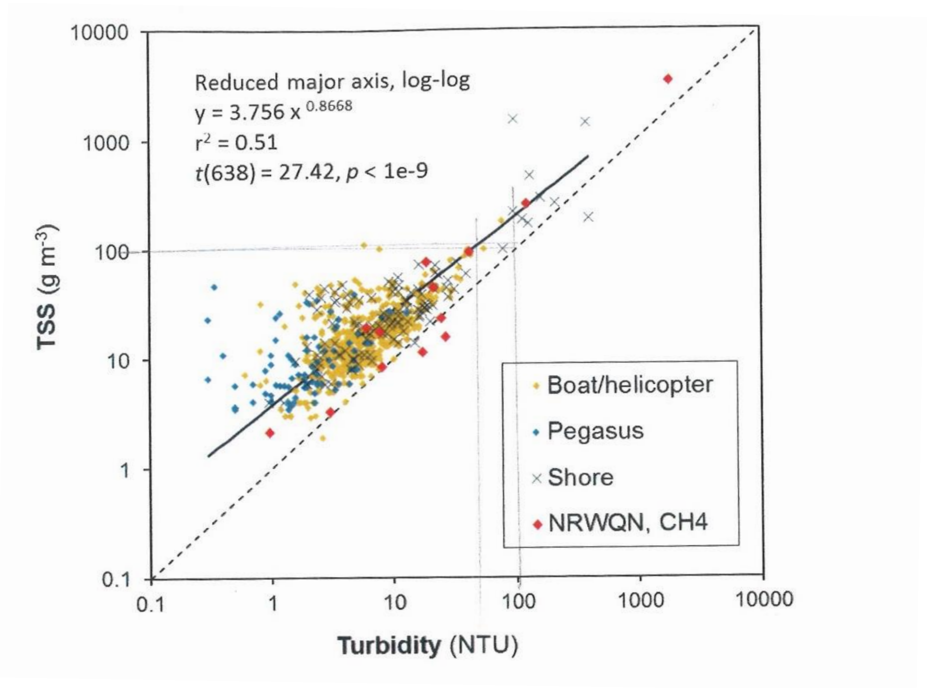


Figure No 16

5. If the FTU number in the bottom turbid layer in a swell event – example 19 August 2004 - is taken as an average of FTU 80 the suspended solid content is .191 gm/m^3 from the CRL analysis of OCEL's sample,

.170 g/m^3 from the ECan regression line. In the area of the outer harbour, from Lyttelton to the Heads, the weight of sediment in the bottom turbid layer can be approximated as in excess of 4000 tonne.

7.5 Turbidity Currents

1. Dense suspensions of suspended sediment, unlike low concentration suspensions are not transported solely by tidal flow. They are also driven by gravitational and rheological mechanics which can advect the suspension across the bed with minimal vertical mixing and settling until a balance of forces arrests the suspension.

2. Gravitational turbidity or density currents are a possible transportation mechanism for the harbour sediments once they are in suspension. While down slope turbidity flows will be a factor in the movement of suspended sediment they will not be dominant due to the relatively low driving force provided by the low slopes. The areas of greatest siltation in the channel however are directly opposite the dumping grounds.

3. Turbidity currents are a key process following a drop of the dredged sediment down through the water column, as occurs when the dredge opens the hopper doors to dump a load. This mechanism was investigated as part of the earlier 2003 study and this study by tracking the movement of the turbidity plume resulting from the dumping of a hopper load of dredged material from the maintenance dredge Pelican. For the 2007/2008 study two dumps were undertaken at the proposed new dumping location for the capital dredging material 4 nautical miles off the Heads and one dump near Godley Head. These dump trials are reported in Section 6.2.

4. Separately, in a second component of the turbidity study, an OBS turbidity meter was used to determine the relative levels of turbidity in the harbour under calm sea conditions, while the dredge was operating and during swell conditions. No correlation was established between turbidity levels in the harbour and the maintenance dredging operation apart from in close proximity to the dumping ground.

7.6 STFATE and MSL Models

1. The dumping process and distribution of sediment was modelled using the Short Term FATE (STFATE) computer program developed by the Coastal Engineering Research Centre (CERC) in the USA. STFATE was used to model the behaviour of the dredged material for dump 2. Figure Nos 17 and 18 show the comparison of the ADCP study and the STFATE model plume results at 17 m water depth and at the surface respectively for dump 2. The modelled footprint is similar - Figure No 19 - to the extent modelled by the ADCP. The mound trail towards the south east indicates material falling out of suspension as the plume moves with the prevailing current. The model gives a good representation of the dispersion of the dredged material during the dumping phase.

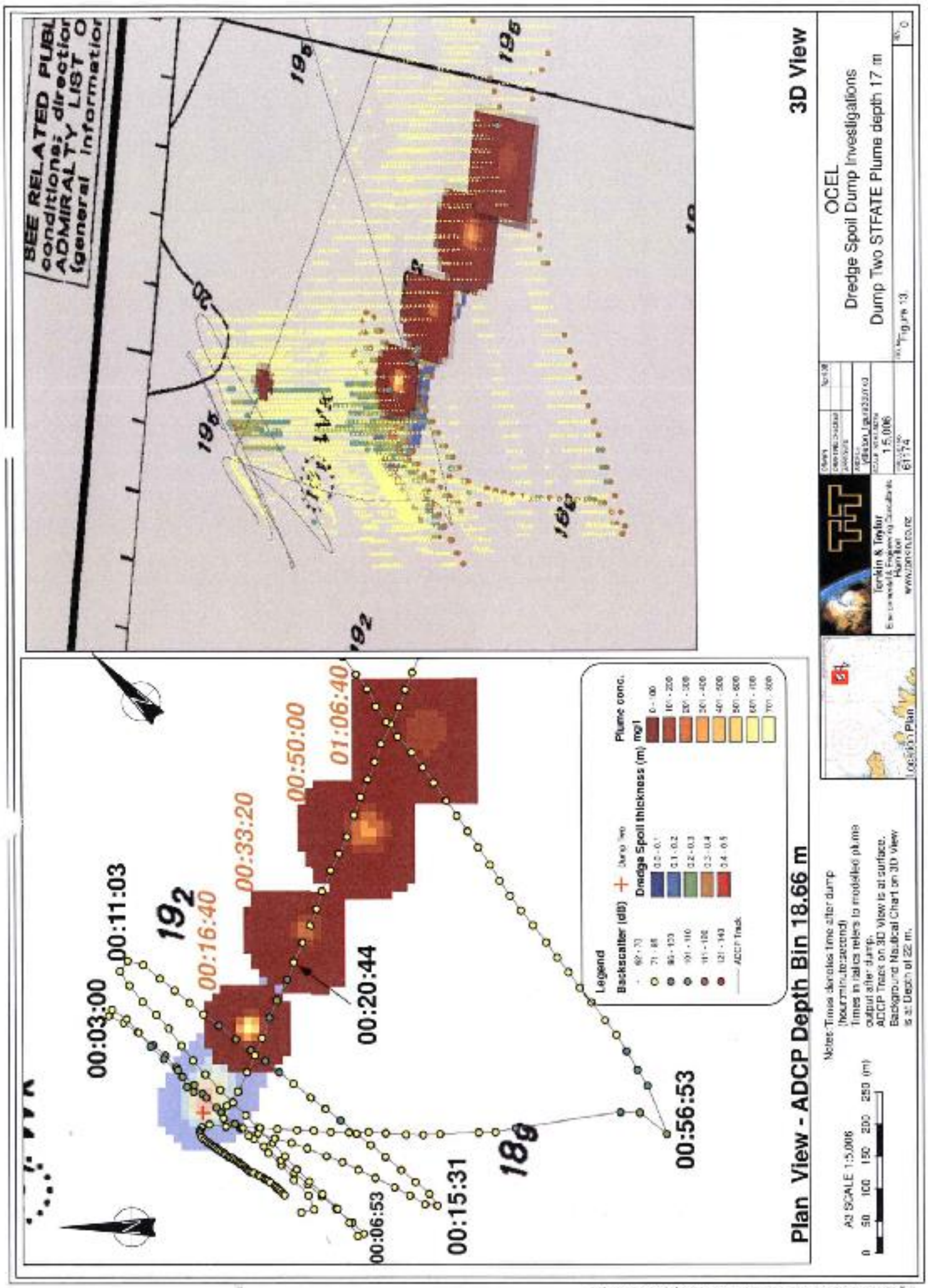

3D View
OCEL
Dredge Spoil Dump Investigations
Dump Two STFATE Plume depth 17 m
Plan View - ADCP Depth Bin 18.66 m
00:03:00
00:11:03
00:16:40
00:33:20
00:20:44
00:50:00
01:06:40
00:06:53
00:15:31
00:56:53
Legend
Plume conc.
Tonkin & Taylor
Location Plan

Figure No 17

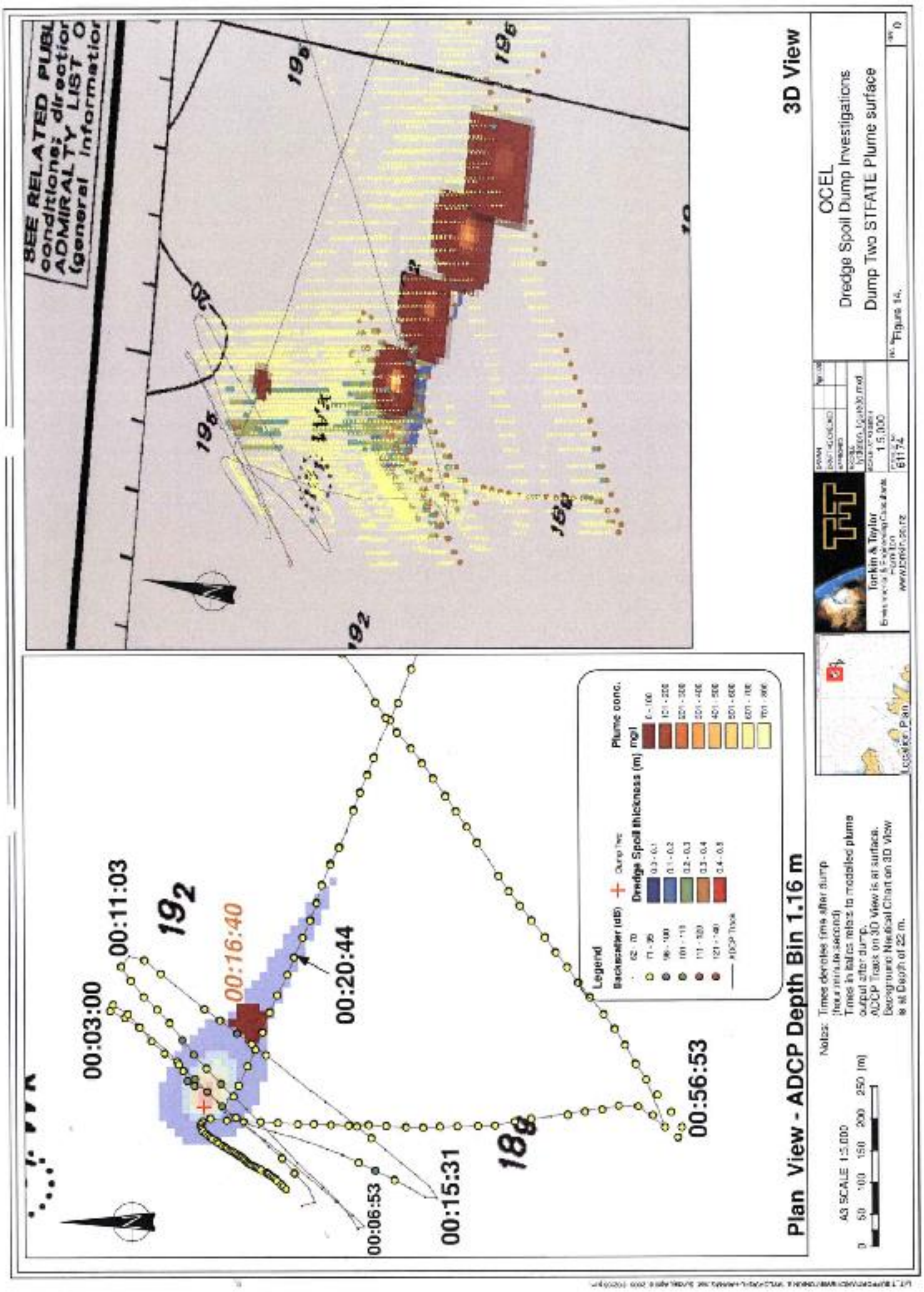

3D View
OCEL
Dredge Spoil Dump Investigations
Dump Two STFATE Plume surface
Tonkin & Taylor
Plan View - ADCP Depth Bin 1.16 m
00:03:00
00:11:03
00:16:40
00:20:44
00:56:53
00:06:53
00:15:31
Legend
Plume conc.
Dredge Spoil thickness (m)
Location Plan

Figure No 18

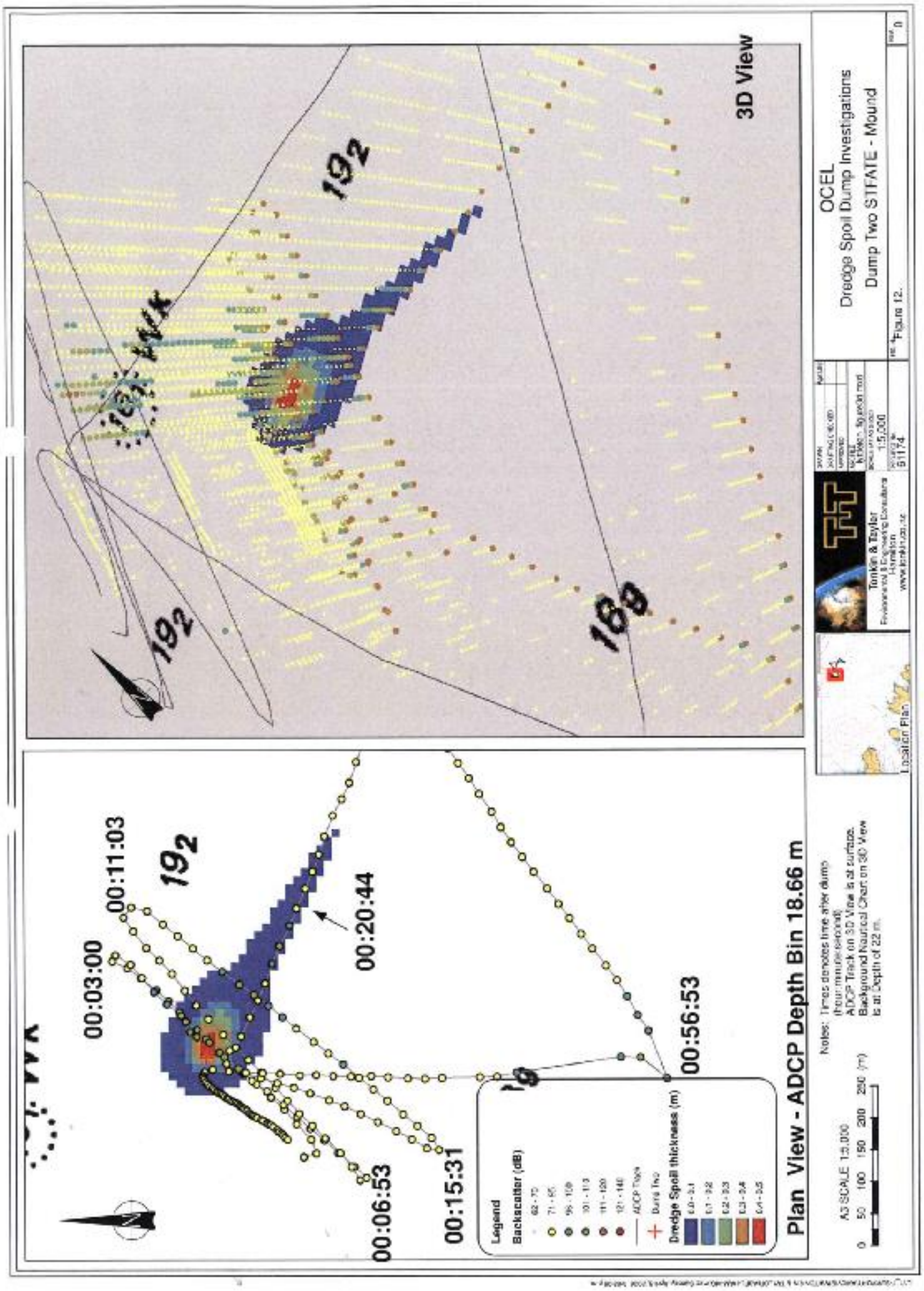

3D View
OCEL
Dredge Spoil Dump Investigations
Dump Two STFATE - Mound
Tonkin & Taylor
Plan View - ADCP Depth Bin 18.66 m
00:03:00
00:11:03
00:20:44
00:56:53
00:06:53
00:15:31
Legend
Backscatter (dB)
Dredge Spoil thickness (m)
Location Plan

Figure No 19

2. The speed of the turbidity current as it spreads out radially and horizontally from the dump point was given by the STFATE model for the 'Pelican' dump trials. The current speed of the leading face of the turbidity plume 82 seconds after the dump was .73 m/sec at a distance of 60 m from the dump centre. After 16 minutes had elapsed from the dump time the speed of the plume face had decreased to .33 m/sec at a distance of 330 m from the dump location.

3. Having established the ability of the STFATE model to predict the dispersion of the dredged material dumped from the maintenance dredge, Pelican – hopper/dump capacity 970 m^3 – STFATE was used to model the dispersion of a hopper load dumped from a capital dredge-hopper capacity 12,000 m^3. Although this latter volume is an order of magnitude greater than the maintenance dredge dump volume modelled and verified against ADCP tracking there is no suggestion of a scaling limitation on the STFATE results.

4. The model output for the large CDP volume and its comparison with the output for the maintenance dump volume is given in Figure Nos 20 and 21. The maximum thickness of the dumped sediment is higher for the 12,000 m^3 drop at 0.6 m versus 0.4 m for the 470 m^3 drop but disproportionately so. There is an insignificant difference in the height of the dumped and dispersed material on the seabed but the footprint is far larger as shown.

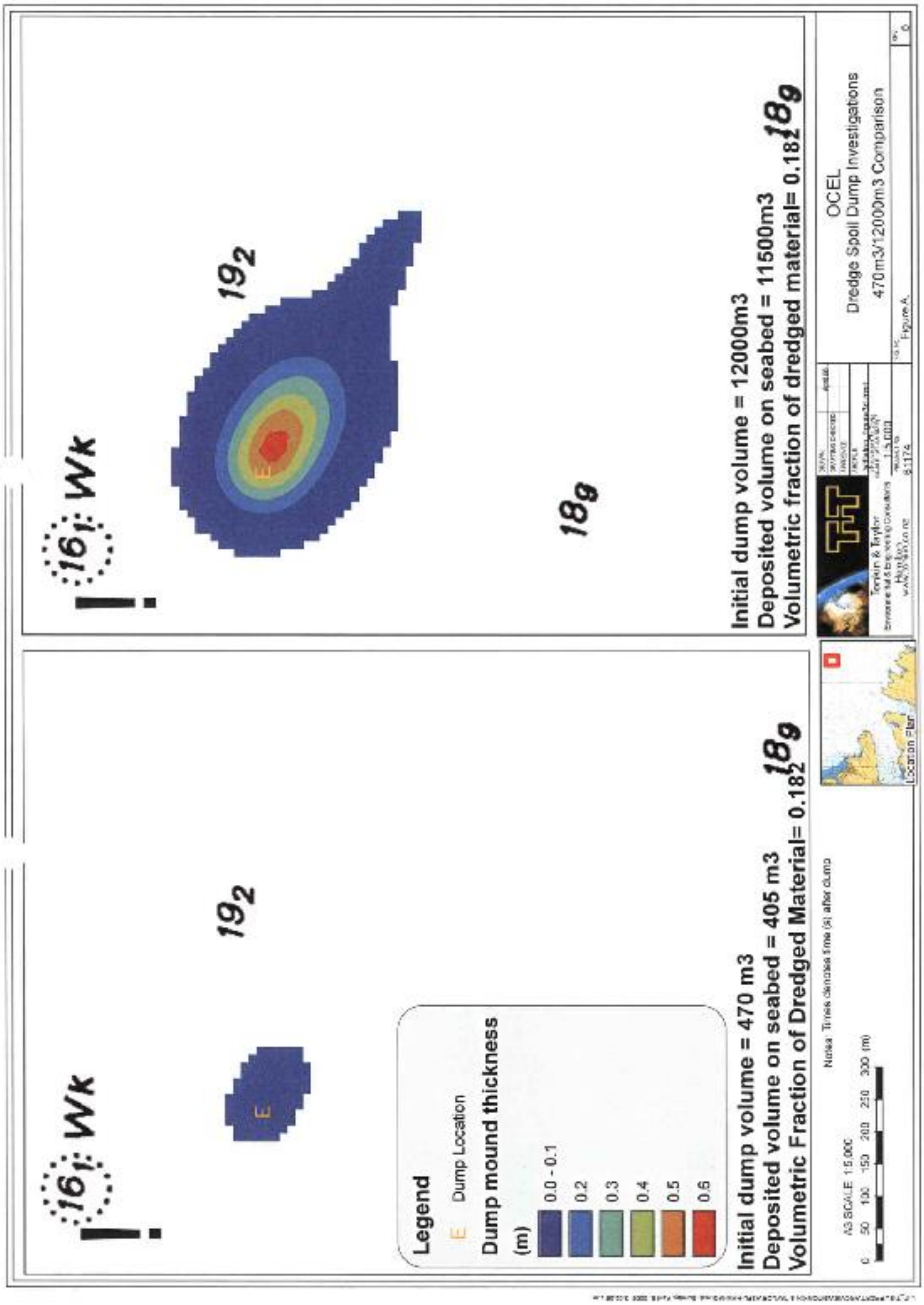

Legend
E Dump Location
Dump mound thickness (m)
0.0 - 0.1
0.2
0.3
0.4
0.5
0.6
Initial dump volume = 470 m3
Deposited volume on seabed = 405 m3
Volumetric Fraction of Dredged Material= 0.182
Initial dump volume = 12000m3
Deposited volume on seabed = 11500m3
Volumetric fraction of dredged material= 0.182
A3 SCALE 1:5,000
0 50 100 150 200 250 300 (m)
Location Plan
OCEL
Dredge Spoil Dump Investigations
470m3/12000m3 Comparison
Tonkin & Taylor

Figure No 20

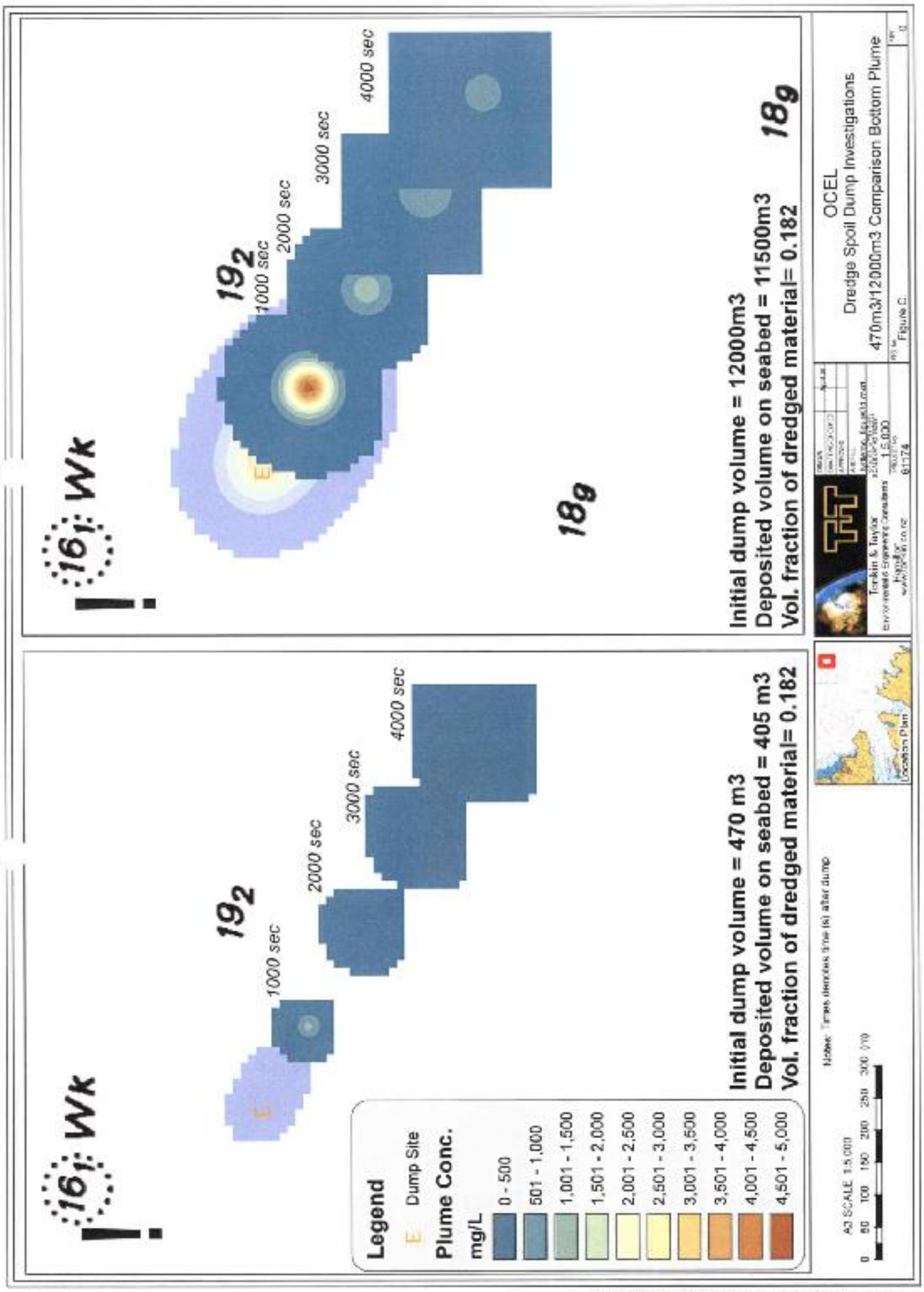


Figure No 21

5. MSL was commissioned by the LPC to undertake a numerical model study to investigate the morphological effects and associated sediment transport patterns associated with the disposal of the CDP material at the offshore dump site.

6. The Delft3D modelling suite coupling high resolution, wave, flow and sediment transport models was applied to the study site to simulate the fate of cohesive sediment dumped at the offshore dump site. The MSL work encompassed the short term fate of the sediment modelled by STFATE and extended it to the long term, 1 and 5 years. The results for the short term were closely similar to the MSL results.

7. The MSL model was used as a tool to qualitatively, investigate the key drivers and patterns of morphological changes at the dump ground over both 1 and 5 year periods. The qualitative as opposed to the quantitative assessment for the long term is appropriate given the lack of data to validate the model. The long term predictions were different from the earlier work by OCEL and Mulgor to the extent that while all the studies were based on sediment disturbance by wave action then transport by tidal currents the MSL work included the effects of wave mass transport. The MSL net sediment spreading footprint was skewed to the north west as a result of the wave action the OCEL/Mulgor work, which did not allow for wave mass transport, predicted a skew to the south east.

8. Wave mass transport in relatively deep water – eg over the offshore dump site – is a second order effort only becoming significant in, and close to, the surf zone. However, the effect is directly related to wave height and in episodic high seastate events can become significant – which is what the MSL model is indicating. This is a relatively minor difference as neither of the models show sediment coming inshore it is spread parallel to the coastline. In any event fine sediment silt and clay would not settle out in the near shore environment even if the material was moved close inshore. The high energy wave environments close to shore make that impossible. This is consistent with the fact that all the fine material discharged by the Waimakariri River over centuries has gone offshore and not settled on the Christchurch surf beaches, even though turbidity currents carry it south.

8.0 ENVIRONMENTAL FACTORS INFLUENCING SEDIMENT MOVEMENT

1. The primary influences on sedimentation and channel siltation within and outside the harbour are the waves and tidal currents. While wind (local wind as opposed to wind blowing over distant wave fetches to produce swell) can induce surface currents in the same direction as the wind, current speeds 2-3% of wind speed, the wind driven current is primarily a surface current that drops off rapidly with depth and has little significance for sediment disturbance and movement in the outer harbour and Pegasus Bay. Locally generated wind waves are short period and do not affect the seabed.

8.1 Wave Energy Environment

1. The wave climate both within and outside the Lyttelton Heads is relatively benign – compared to elsewhere on the New Zealand coastline – both in terms of the height of the wave experienced offshore and the frequency of occurrence of big sea conditions. It has no exposure to the waves generated by the prevailing westerly winds over essentially unlimited fetch lengths to the south west of New Zealand. While there is not the same long period swell background on the east coast as on the west coast depressions off the east coast can create severe weather and seastate events. Such events however are infrequent.

2. Waves within Pegasus Bay generally fall into two categories, locally derived wind generated waves (typically 3 to 5 seconds period) and swell waves (typically 8 to 20 seconds period) from more distant storms in the southern ocean which refract around Banks Peninsula. The wave directions exhibit seasonal variations with north-east waves prevailing in summer and south-east waves predominating in winter. Longer calm weather windows are generally available in the summer period when extreme weather events are less likely, however, periods of complete calm occur in early to mid winter.

3. Lyttelton Harbour being relatively long and narrow effectively acts as a wave direction filter and only waves aligned with the harbour axis can pass up the harbour. In reality this is not much of a restriction on wave energy as long period swell waves from the south/southeast can refract around Banks Peninsula to run straight up the harbour. Only waves from the north/north northeast are filtered out by the harbour axis alignment and break on the southern shore of the harbour.

4. Wave probability, height exceedance and directional data derived by Mulgor are given in Table No 2 below for a site at the start of the proposed channel just outside the Heads in 16 m water depth. For the highest 1% of waves, significant wave heights exceeding 2.16 m > 95% come from the north east and east north east.

	Wave Height Exceeding m			
Direction	**>0.76**	**>1.65**	**>2.16**	**>2.86**
N	4.6	0.1	0.0	0.0
NNE	10.3	5.2	1.2	0.0
NE	19.5	32.6	46.9	60.0
ENE	38.6	51.0	48.6	34.4
E	10.8	9.2	3.2	5.6
ESE	1.6	0.6	0.0	0.0
SE	0.9	0.3	0.0	0.0
SSE	0.6	0.2	0.0	0.0
S	0.8	0.2	0.0	0.0
SSW	1.4	0.3	0.0	0.0
SW	2.2	0.1	0.0	0.0
WSW	2.2	0.1	0.0	0.0
W	1.0	0.0	0.0	0.0
WNW	0.9	0.0	0.0	0.0
NW	1.5	0.0	0.0	0.0
NNW	3.0	0.0	0.0	0.0
% of time	50.0	5.0	1.0	0.1

Table No 2

5. The wave data was generated by D Goring of Mulgor using the National (USA) Oceanic and Atmospheric Administration (NOAA) NWW3 (NOAA Wave Watch 3) global wave model to derive, hindcast, wave parameters – significant wave height H_s, peak period Tp and direction for a deep water site offshore Banks Peninsula. A wave refraction analysis using the Simulating Waves Nearshore (SWAN) wave model was run to transfer the wave data inshore to the site at the start of the proposed channel.

6. Waves in shallow water produce an oscillatory velocity at the seabed which acts to disturb the seabed sediment by creating bed shear stress. As noted the oscillatory bed shear stress is a function of the square of the water particle velocity. Shallow in this context means approximately

$$d < 0.1gT^2 \quad \text{or alternatively} \quad d < 10.\ H_s$$

where d is the depth of water, T is the wave period and H_s is the significant wave height. Short period locally generated wind waves T_p = 3 – 6 seconds period, only effect the seabed in the upper reaches of the harbour. Long period swell waves, 10-12 seconds can reach and disturb the seabed over the full extent of Pegasus Bay and the harbour inlet apart from the Upper Harbour where the remnant swell waves reaching this area are much diminished in height by bottom friction and diffraction effects.

7. Although monochromatic – uniform wave period – swell wave conditions can be experienced in the harbour the typical sea comprises a spectrum of waves of different heights, wave periods and directions. This produces a random time series of orbital velocity at the seabed. The seastate can be characterised by the significant wave height H_s, and the zero upcrossing period T_z where $T_z \approx 0.71.T_p$,. the peak wave energy period.

8. The wave induced water particle velocity at the seabed produced by the significant wave height can be calculated using the applicable wave theory for the particular combination of wave height, period and water depth. For a 1 m high 12 second period swell wave in 16 m water depth - at the site for the wave

height exceedance data given (Table No 2) Stokes 5th order wave theory is applicable and the significant water particle velocity U_s at the seabed is .34 m/sec.

9. This water induced water particle motion is sufficient, in conjunction with the wave induced pressure fluctuations as the wave crest passes overhead, to mobilise fine sand and silt into suspension. From Table No 3 significant wave height exceeds 0.76 m significant 50% of the time but since locally generated short period NE/ENE wind waves can easily attain this height the swell waves capable of entraining the seabed sediment will only be a small proportion of the 50%. The distribution by period (%) of waves that exceed various significant wave height for the site at the start of the proposed channel are given in Table No 2 below. For the NE/ENE waves higher than 2.16 m approximately 30% have periods greater than 10 seconds.

	Wave Height Exceeding m			
Peak Period s	**>0.76**	**>1.65**	**>2.16**	**>2.86**
<=7.4	64.2	30.2	36.0	14.40
8.3	7.4	12.4	22.9	38.9
9.4	9.7	8.1	10.6	24.4
10.6	10.2	15.3	7.9	10.0
12.0	6.0	23.6	10.8	12.2
13.6	1.9	10.0	11.8	0.0
15.3	0.5	0.4	0.0	0.0
>=17.3	0.1	0.0	0.0	0.0
% of time	50.0	5.0	1.0	0.1

Table No 3

Distribution by period (%)of waves that exceed various heights,
for node ltc1 at the entrance to the harbour

10. A 0.76 m significant wave height 12 second period swell wave produces a significant on bottom water particle velocity of 0.26 m/sec in 16 m water depth. The significant wave height is the average of the 1/3 highest waves. While this is just less than the approximate erosion velocity for silt, 0.3 m/sec, the largest swell waves of a swell wave spectrum characterised by H_s = 0.76 m will be capable of entraining the seabed sediment in 16 m water depth. Since H_{max} (U_{max}) can be taken at 1.8 H_s (U_s) for a 4 hour period.

11. Inside the Heads along the 10 m depth contour the water particle velocity produced at the seabed by a 1 m significant swell wave height, wave period 12 secs is 0.49 m/sec; even the smaller swell wave heights in a seastate characterised by H_s = 1 m, T_p 10 – 12 secs can entrain bottom sediment. In contrast a 1 m high 4 second period wind wave in 10 m of water produces a water particle velocity of .08 m/sec, insufficient to entrain sediment.

12. Swell waves in excess of 1 m significant wave height and 10 – 12 second period can disturb and entrain sediment over the full extent of the harbour inlet and outside it, including the proposed dump location. The locally generated wind waves cannot, they have minimal effect on harbour siltation other than at the Head of the harbour.

13. The height of swell waves passing up the harbour decreases primarily as a result of bottom friction and diffraction effects. Figure Nos 17 and 18 taken from MSL reports show the decrease in swell wave height with distance from the harbour entrance.

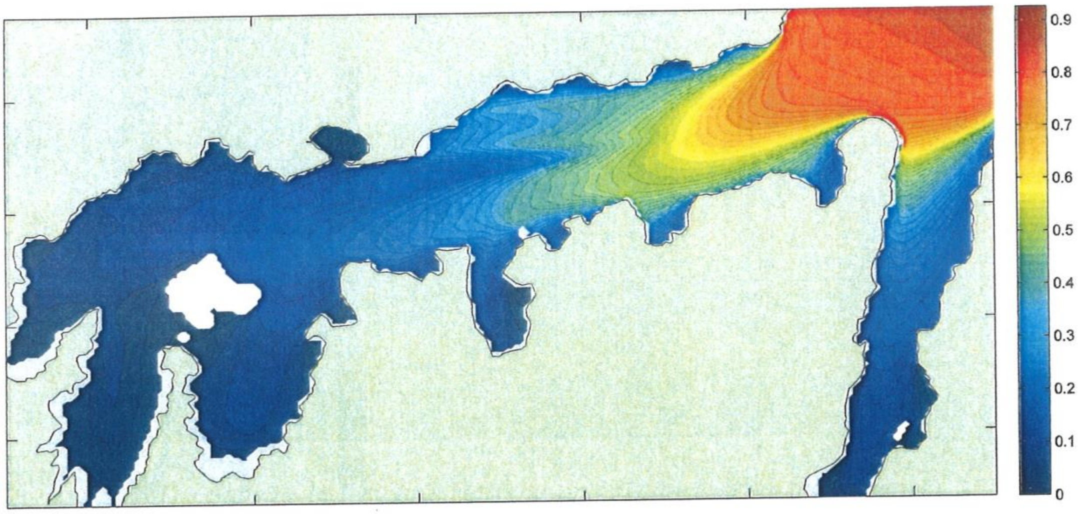


Figure No 17

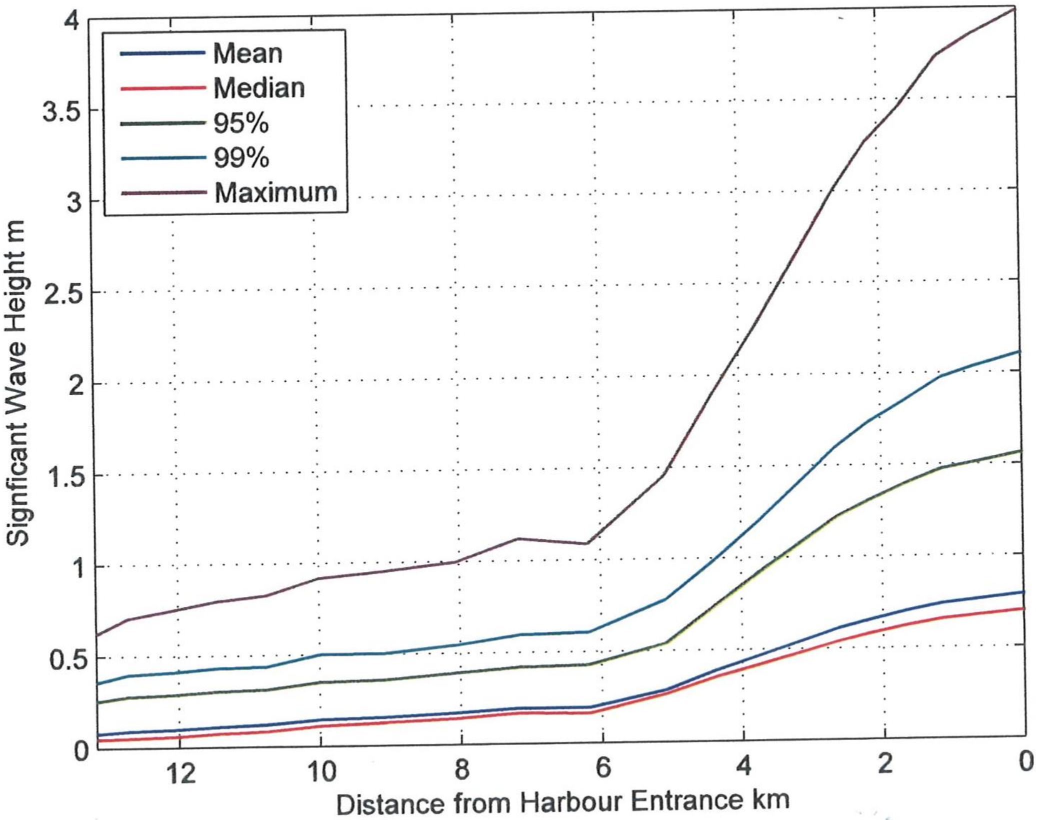


Figure No 18

14. In the head of the harbour off Rapaki the significant wave height for remnant swell waves reaching the location has decreased to the order of 0.15 m. The water particle velocity at the seabed has deceased 0.1 m/sec and is not capable of disturbing the seabed.

15. A 1m high locally generated wind wave can affect the seabed and entrain sediment. The on bottom water particle velocity is in excess of 0.3 m/sec. Figure Nos 19 and 20 show a graphical comparison of relative wave effects at the Heads and off Rapaki.

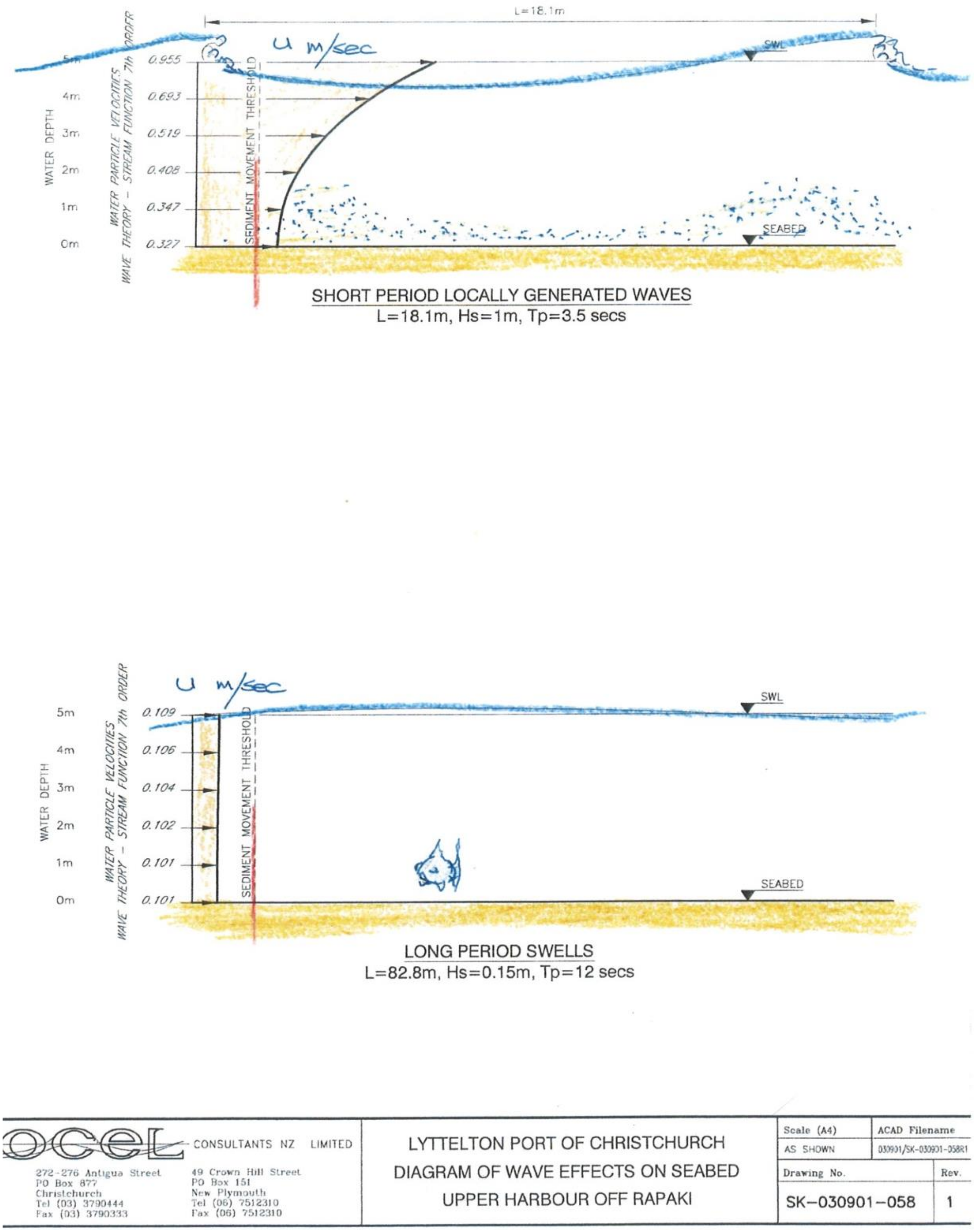


Figure No 19

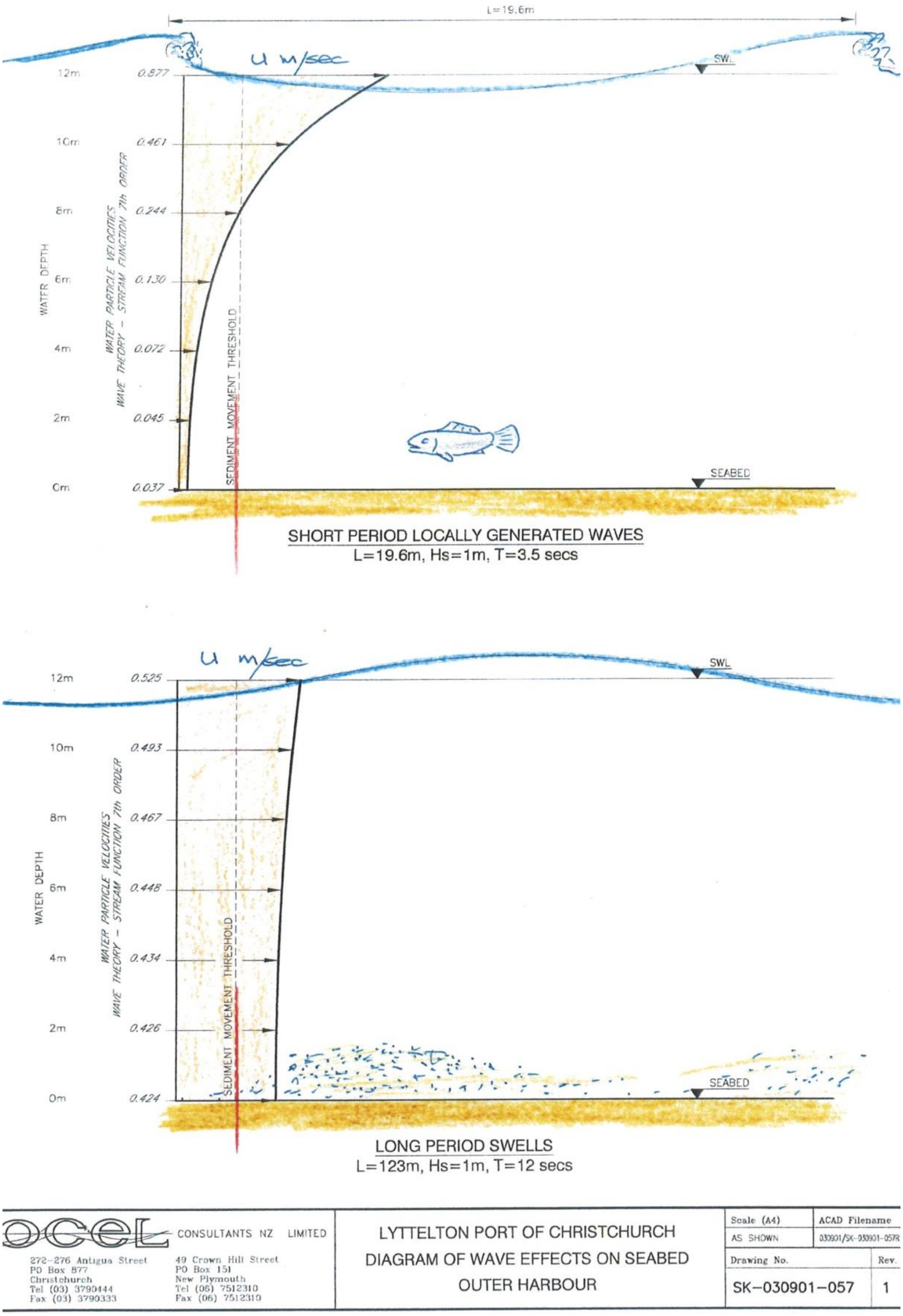


Figure No 20

16. At the proposed dump location in 20 m water depth only seastates characterised by significant swell wave heights in excess of 1.2 m and periods greater than 10 seconds are capable of causing significant disturbance to the seabed. A 10 second period 1.2 m high wave produces a water particle velocity of 0.30 m/sec in 20 m water depth.

17. As the height and steepness of the waves increases the velocity under the crest, directed onshore, is greater than the velocity under the trough, directed offshore, and there can be movement onshore. For a 6 m high wave in 16 m water depth the velocity under the crest is 2.2 m/sec. and the reverse velocity under the trough is 1.45 m/sec., calculated using Stokes 5th order wave theory.

18. A 6 m significant wave height corresponds to close to the 50 year return period significant wave height for inshore Pegasus Bay. The maximum wave height in a 4 hour period for a seastate characterised by H_s = 6 m would be of the order of 11 m. The high water particle velocity, well in excess of the minimum entrainment velocity, is associated with an increasing height of turbulence up off the seabed. The effect of this is to distribute sediment throughout the water column. The wave directions are not particularly significant. The waves and swell action entrain the sediment into suspension making it available to be transported by tidal currents.

19. While wave motion is commonly thought of a purely oscillatory – and it is for simple sine waves that can be used to approximate long period low height swell waves in deep water – mass transport, movement of water, permanent displacement of water particles in direction of wave approach occurs for finite height waves in shallowing water, as the wave starts to feel the seabed. This starts when the water depth is less than half the wave length.

20. The wave water particle orbits are circular in deep water and increasingly elliptical in shallower water. Linear, Airy or Sinusoidal wave theory does not hold when the wave amplitude is non negligible compared to the wave length or depth. As the wave amplitude increases the wave crest becomes increasingly peaked while the trough flattens out.

21. For a 2 m high, 12 second period swell wave in 10 m water depth the crest height is 1.27 m above still water level (SWL) and the trough is .73 m below (7th order Stream Function theory), rather than equi-distant above and below SWL as for a sine wave. The bottom velocity under the crest for the finite amplitude wave is 1.02 m/sec and .69 m/sec under the trough.

22. For finite amplitude waves the water particle orbit is not truly elliptical. Due to the co-variance of the oscillating water surface and orbital velocity, the crest position of the water particle at the end of the cycle shifts in the direction of wave travel compared to the beginning of the cycle. Effectively the loop isn't closed; the difference in end position is the Stokes drift. There is a net transport of water mass in the direction of wave travel with an associated horizontal velocity, the Stokes drift or mass transport velocity, u_s. It is a maximum at the surface and decreases exponentially with depth.

$$u_s = 0.5 \cdot C_w \cdot k^2 \cdot a^2 \cdot \{\cosh(2 \cdot k \cdot (h + z))/\sinh^2(k \cdot h)\}$$

where:
- C_w is the wave celerity = L/T
- h is the water depth
- a is the wave amplitude
- z is the distance from SWL, down -ve
- $k = 2 \cdot \pi/L$
- $\omega = 2 \cdot \pi/T$

23. For a 2 m high 12 second period wave in 10 m water depth, L = 115.7 m (from 7th order Stream Function theory) the mass transport velocities are as follows;

z = -10	u_s = .0437 m/sec
-9	.0439
-8	.0447
-7	.0460
-6	.0479
-5	.0503
-4	.0533
-3	.0569
-2	.0613
-1	.0664
0	.0721

Table No 4

This confirms the second order nature of the effect, the mass transport velocities are much less than the tidal current velocities and much more infrequent.

The water discharge associated with the drift is found by integration over the water depth

$$q_{drift} = \pi \cdot H^2/(4 \cdot T) \cdot (1/\tanh(k \cdot h))$$

Using the values for a 2 m high 12 second period wave - q_{drift} = .5 $m^{3/}$sec/m of crest. The bulk of this discharge is close to the surface, the sediment concentration expressed as turbidity NTU values is closer to the seabed. For waves entering the harbour this inward mass transport has to be matched by an outward flow close to the seabed.

24. While mass transport effects are second order effects the latest modelling of fine sediment transport by MSL, as part of MSL's Maintenance Dredging Report 2016, indicates that sediment transport of fine sediment both inside and outside is not exclusively the preserve of tidal currents. Wave action is still the determinant of sediment mobility but mass transport effects in high seastate conditions move large volumes of sediment in major episodic events. The transport is due not just to mass transport velocities but also due to the pile up of water against the Godley Head cliffs by the associated water discharge in the direction of wave advance. Currents develop as a result of the increase in hydraulic head against the cliffs and water flows out and away producing currents. Further work is being undertaken by MSL to isolate these current effects for comparison with the tidal current velocities.

8.2 Tidal Currents

8.2.1 Background

1. OCEL has undertaken a number of investigations of tidal currents in Lyttelton Harbour over many years both for vessel handling studies and sediment transport work. OCEL studies in 2000, 2003 and 2007/2008 have used the ADCP in both the mobile and static modes. These studies have been complemented by physical drogue tracking work in rougher seastate conditions than are possible to work with the ADCP in mobile mode.

2. The advent of the ADCP instrument and concomitant increases in the power of modern computers has revolutionised the collection of environmental data making it possible to gather and process huge amounts of data in a relatively short space of time. There are no moving parts, no propellers or rotors. In the static mode the ADCP is set in position at one point and measures the current speed and direction at that point. In the mobile mode the ADCP looks downward off the side of the survey boat while the boat is in transit.

3. The ADCP unit, mounted either on the side of a boat or set in one position on the seabed, measures the current speed and direction over practically the entire water column, either below the boat while the boat is in transit or looking upward to the surface while mounted on the seabed. This is performed by

measuring the scattered acoustic signal reflected by particulate matter in the water column together with the Doppler effect.

4. In the mobile mode an ADCP instrument is deployed from a survey boat run non stop around a 5 nautical mile circuit at 5 knots over the full length of a tidal cycle, 13 hours. Each point on the circuit is crossed once an hour. A specialised and sophisticated form of tidal analysis is used to develop estimates for the tidal current in between measurement times. The method assumes that tidal currents are spatially represented by bi-harmonic splines and in time by sinusoids.

   The ADCP is interfaced through onboard computers with a DGPS navigation system to attribute geographic coordinates to each velocity vector measurement. The positioning/navigation system also determines the vessel's velocity and this is removed from the measurements to derive the current speed over ground.

5. The OCEL tidal current survey work undertaken in 2003 using the ADCP in the mobile mode identified the tidal circulation patterns in the outer harbour in particular the development and persistence of the vortex that forms inside Godley Head on the incoming tide. This work gave the first detailed picture of tidal circulation in the outer harbour confirming the asymmetry of the tidal flow.

6. Tidal flow in and out of Lyttelton Harbour is not a simple uniform flow in and a corresponding ebb flow out, there is a pronounced asymmetry to the tidal circulation. This asymmetry in the flow was known from earlier work. Garner and Ridgway remarked on it in 1955 following experiments with floats and fluorescein and later work in the 1970's by Bushell and Teear for the LHB confirmed it and quantified a tidal imbalance on the north side of the harbour. Although the magnitude of the ebb and flood tide currents were found to be similar the ebb tide volume and duration exceeded those for the flood (up to 30%). The duration of the flood tide on the south side of the harbour was found to be more than for the ebb.

7. R J Curtis in his doctoral thesis entitled 'Sedimentation in a Rock-Walled Inlet, Lyttelton Harbour' produced in 1985, built on the earlier work on asymmetric flow. He noted the generally clockwise circulation imparted by the tidal imbalance either side of the harbour and postulated the existence of large scale tidal gyres in the outer harbour. One of the objectives of the 2003 study was to provide data to close gaps in the knowledge of the harbour regime and to either confirm or deny the existence of Curtis' gyres.

8. The tidal imbalance can be expressed as a tidal residual which corresponds to the average movement at a location over the full tidal cycle. The tidal residual indicates the net direction in which a notional particle rolling on the sea floor would move. It indicates a net movement or pumping effect the implications of which are of importance for the movement of suspended sediment.

9. The finding of a net flow out on the north side of the harbour supported the move to dump dredged material on that side in an effort to increase wave refraction effects. More would be flushed out on the ebb than carried in on the flood. The tidal residuals on the north side of the harbour are directed east while those on the south side are directed west. This imparts a weak clockwise circulation to the harbour. The circle is not however closed by a tidal gyre at the entrance to the harbour as conjectured earlier by Curtis. Large scale tidal eddies develop fully at two locations in the harbour: in the region of the Cashin Quay breakwater and inside Godley Head. The breakwater and Godley Head constitute two major obstructions to the flow and vortices or eddies form in their lee.

10. The formation of an eddy in the lee of Godley Head is a direct result of the northerly aspect to the flood tide flow into the harbour. The Godley Head eddy is not the tidal gyre postulated by Curtis. It is less in scale than the one he proposed, stays close to the north shore of the harbour and does not extend across the complete width of the harbour. It also rotates clockwise, not counter clockwise, on the flood and does not reverse on the ebb.

11. The eddies act to speed up the tidal flow in their immediate vicinity, on the side where the flow has the same direction as the prevailing flow. For example the residual clockwise rotating flood tide eddy inside

Godley Head acts to speed up the ebb tide current on its north side. Any suspended sediment caught in it will be ejected from the harbour. Other eddies start to form at various stages in the tidal cycle, off Purau and off Breeze Bay, but do not develop fully.

12. The variation of current with depth was found to be generally close to a block profile, relatively unchanged with depth, in line with earlier assumptions, although at some of the locations at some of the time the currents at the top and the bottom of the water column can be markedly different. Previous work carried out by OCEL and Bushell and Teear using a Braystroke direct reading current meter had earlier validated the assumption at a limited number of points in the harbour west of the Cashin Quay breakwater.

13. While the direction of the tidal streams is generally along the axis of the harbour the flood tide was found to have a small angle to the navigation channel in the outer harbour. The drogue studies indicated more of an angle than the ADCP work. Close to the major flow obstruction represented by the breakwater the flood tide flow along the north side of the harbour crosses over to the south side of the harbour to go around the breakwater. Suspended sediment will be carried over the channel.

14. The tidal exchange at the Heads is not a simple block movement in and out of the harbour with little exchange of the water further up the harbour. The movement of water in and out of the harbour with the tide is only a block motion at certain phases of the tidal cycle once the ebb and flood tide flows have been established. Prior to that the strength of the tidal currents varies markedly across the entrance being generally stronger at the sides of the harbour, particularly on the ebb where the flow is strongest closest to Godley Head. A jet can form there which breaks up the block movement and can take the water in the jet far enough away so that it does not return on the flood. The asymmetry of the flows within the harbour and general clockwise circulation promotes mixing within the harbour and with the water of Pegasus Bay.

8.2.2 Tidal Compartments

1. The relatively low tidal current speeds (1 knot) and the consequent limited tidal excursion distances on a tide – typically of the order of 3.5 km maximum, as determined both by drogues and neutrally buoyant particles released in the MSL hydrodynamic models – mean that Lyttelton Harbour inlet is effectively compartmentalised into three tidal compartments: outer, central and upper. Approximate locations for the tidal compartments are shown in Drawing No DR-030901-054 – Appendix A. The size of the upper harbour compartment has been confirmed by the results of the mobile telephone equipped self tracking drogue, Figure No 21.

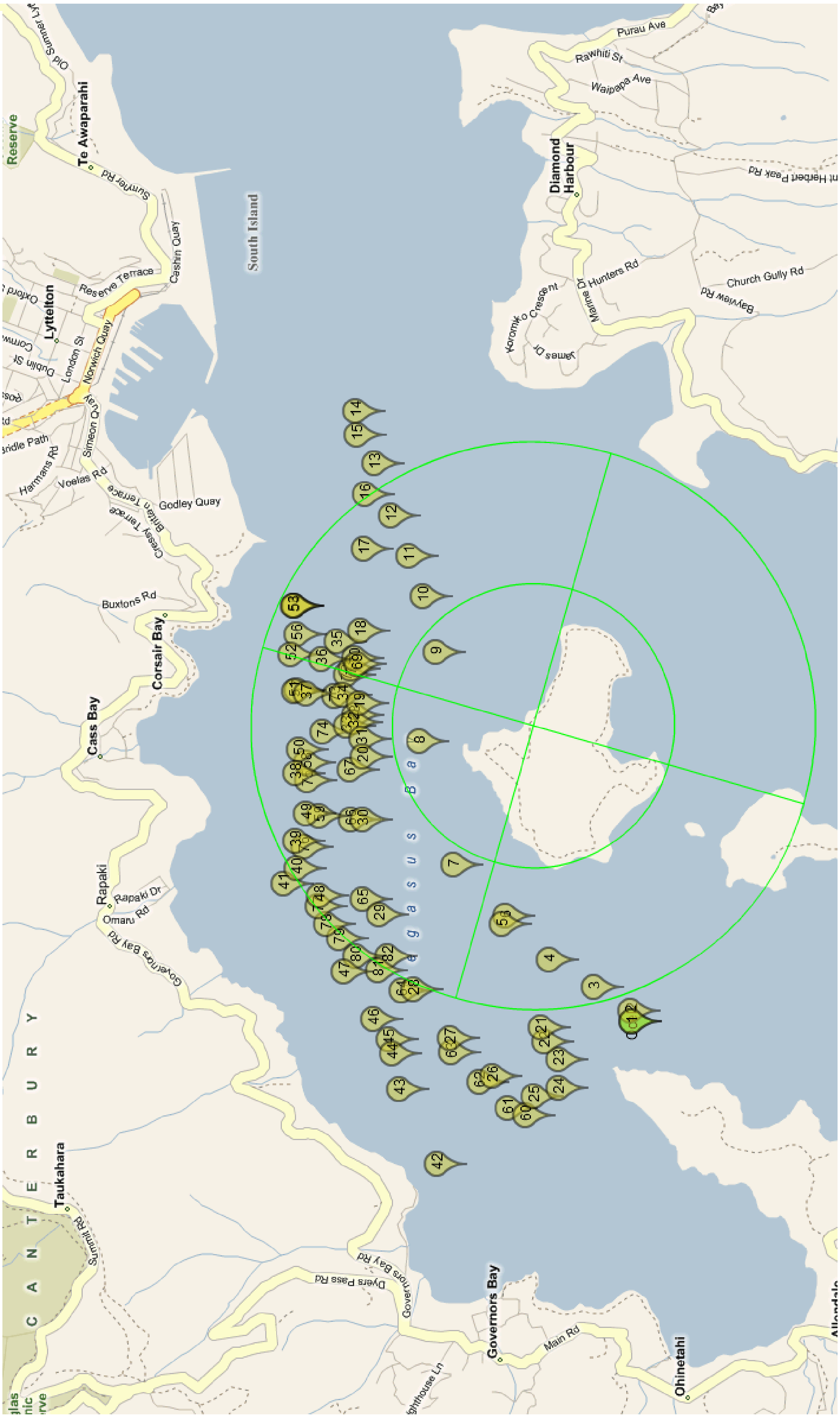

South Island
Diamond Harbour
Purau Ave
Rawhiti St
Waipapa Ave
Hunters Rd
Church Gully Rd
Bayview Rd
Koromiko Crescent
Marine Dr
James Dr
Te Awaparahi
Sumner Rd
Cashin Quay
Reserve Terrace
Lyttelton
Oxford St
London St
Dublin St
Norwich Quay
Simeon Quay
Bridle Path
Harmans Rd
Voelas Rd
Godley Quay
Brittan Terrace
Cressy Terrace
Buxtons Rd
Corsair Bay
Cass Bay
Rapaki
Rapaki Dr
Omaru Rd
Governors Bay Rd
Taukahara
Summit Rd
Dyers Pass Rd
Governors Bay
Main Rd
Ohinetahi
C A N T E R B U R Y

Figure No 21

2. While the harbour has a more or less constant width of 2 km over the greater part of its length as previously noted, tidal flow in and out of the harbour is not a simple block flow in plan view. It does not expand into a large estuary at the head of the harbour thereby greatly increasing the size of the tidal prism relative to the entrance width.

3. Asymmetry of the tidal flow in all three compartments of the harbour however allows the interchange of water between the tidal components, allowing water to ultimately leave the upper harbour. Asymmetry in the tidal circulation predates, and was identified well before, the construction of the Cashin Quay reclamation. The Cashin Quay breakwater acts as a local control feature on the tidal current flows. The breakwater directs the incoming tidal flow out into the middle of the harbour and in doing so promotes the development of a large anticlockwise rotating circulation cell of Cashin Quay. This was shown by the drogue tracking and current monitoring work undertaken by OCEL for the LPC in 2000. The study work was undertaken to gather data for a ship handling model of the port. Single point or 2 dimensional (2d) ADCPs were used in conjunction with drogue tracking. The principal interest was in the tidal currents affecting ship handling in the vicinity of the port.

4. In the upper harbour the strongest tidal currents, 1 knot maximum ebb and flow, occurs in the channel between the Naval Point reclamation and Shag Reef. This introduces an element of asymmetry into the flow. In addition the tidal streams from either side of Quail Island in the upper harbour exit their respective embayments at an angle to each other resulting in mixing. The greatest mixing occurs in the central tidal compartment, opposite the Port.

5. Because of the limited tidal excursion distances it will take some time, several tidal cycles, for the bulk of the water in the upper harbour to leave the harbour system. In an effort to illustrate this a self tracking buoy was released in the upper harbour and tracked over a period of 2 days. The buoy/tidal current drogue carried a Global Positioning System (GPS) capable mobile telephone that automatically reports its position at a given time interval – which was set at 30 minutes for the upper harbour survey work.

   The movement of the buoy could be followed in real time on the mobile telephone tracking website. The buoy was released in Governors Bay on the north side of the Upper Harbour and tracked for two days, during which time it did not leave the Upper Harbour. The excursion track is shown in Figure No 21.

6. The buoy reached as far east as the Diamond Harbour pipeline but was then swept back in by the flood tide and ended up around the back of Quail Island. It did not leave the upper harbour. The wind conditions ranged from light north east to calm. The drogue tracks correspond very well with the trajectories of neutrally buoyant particles released in similar positions during model runs of the MSL SELFE hydrodynamic model.

The buoy was also released in Charteris Bay on the south side of the Upper Harbour and tracked for two days. The wind conditions varied from calm to strong north east. The tidal currents were found to be weaker on the south side of the harbour and the tidal excursion less than on the north side of the Upper Harbour. The buoy track is shown in Figure No 22. The buoy became trapped in kelp fringing Quaill Island three times.

Figure No 22

7. The implications of a relatively long dwell time or changeover time in the upper harbour are reflected in the fact sediment accumulation has continued to occur over the last 50 years in the upper harbour with bed level shallowing of around 0.2 m in the three main upper harbour bays – Hart et al 2008b. The upper harbour area is relatively shallow and subject to sediment disturbance by short period waves generated by strong south west winds sweeping down the harbour. Sediment entrained by these waves remains in suspension the upper harbour area. There is no apparent significant movement of sediment out of the upper harbour area. If there was this would be reflected in the volume of dredged material taken out of the navigation and berthing areas inside the Cashin Quay breakwater.

8. Sediment entrained into suspension either by wave action or dredging activity in the outer harbour cannot reach the upper harbour in one tidal cycle. To get there it has to pass the sediment traps represented by the navigation channel and berthing areas. Only sediment entrained on the south side of the channel can escape the sediment traps on the incoming tide. Any suspended sediment reaching the central compartment is likely to be swept over the navigation channel on the outgoing tide. There is no evidence of any accumulation of sediment or shallowing in the central compartment of the harbour.

9. The source of the sediment causing the shallowing in the upper harbour is likely to be derived from erosion of the local catchment. Transport of sediment from the outer harbour to the upper harbour can be

discounted on the basis of the number of tidal cycles it would take to get there and the sediment traps on the way.

8.2.3 Tidal Models

1. In addition to the earlier ADCP survey work in 2003, 2007 and 2008 the predictions of the NIWA tidal model for the area were checked. The relatively coarse scale of the model meant that it could not provide detail around the harbour entrance Heads but it did give a good indication of the tidal current directions offshore. Dr Derek Goring found an excellent fit between the NIWA tidal model predictions and the data gathered by the ADCP on the proposed offshore dump site for the dredged material from the extended and deepened channel.

2. The MSL report Finite Element Hydrodynamic Model of Lyttelton Harbour Rev A 2011 provided an accurate, validated, model of tidal currents in the harbour, supplanting the NIWA model for the harbour however the NIWA model is still valid, and validated, for the offshore tidal currents. The MSL SELFE model used for the latest tidal current predictions further extends the tidal current modelling and predictive capabilities. Each model evolution has added greater detail. The model results are validated by OCEL's earlier recording work.

3. The earlier MSL Princeton Oceanographic Model (POM) summarised in the Mulgor Report has been used by Dr Derek Goring to develop the trajectories of neutrally buoyant particles over a tidal cycle giving results comparable to the physical drogue studies. The trajectories provide a confirmation of the harbour compartmentalisation discussed in Section 8.2.2.

4. The MSL tidal current model is a powerful tool for modelling changes to the harbour. It can successfully replicate existing tidal current measurements and so can be used with confidence to predict changes to the tidal currents resulting from the dredging work.

9.0 SEDIMENTATION AND CHANNEL SILTATION

9.1 Sedimentation in the Harbour

1. Sedimentation is the conversion of discrete soil particles in a suspension into loose sediment. R Curtis researched the background of the history of sedimentation in the harbour as part of his PhD thesis (1985) and provided an assessment of sedimentation and dredging effects in the harbour to the LHB in 1986. From a comparative study of hydrographic charts and dredging records over time it is apparent that the harbour is in a state of quasi-stability in terms of net sedimentation.

2. The hydrographic survey data collected by the LPC over time as part of the routine monitoring of the maintenance operation dredging and the dumping areas confirms the quasi-stability.

3. Curtis calculated the quantity of new sediment entering the harbour each year, principally as a result of the erosion of loess, at between 16,000 and 44,000 tonnes per year. This occurs primarily at the Head of the harbour. While this is a significant volume it pales in comparison to the quantities of fine sediment involved in internal recirculation in the harbour each year.

4. The major sedimentary process within the harbour is the maintenance dredging program which removes in the order of 1 million tonnes per year from the navigation channel. He estimated for the harbour as a whole that the total quantity of sediment involved in transport and sedimentation each year was between 700,000 and 1 million tonnes. There is an apparent clear link with the maintenance dredging operation. Note that this is the sediment being transported and trapped by the navigation channel.

5. Irrespective of the dredging operation the harbour seabed is disturbed by swell induced water particle velocities at seabed level disturbing the sediment and entraining it into suspension. Large volumes will be in suspension naturally but not trapped. Once the fine materials have been suspended the sediment can then be moved by tidal currents. In the natural state this results in a flattening or levelling of the harbour seabed.

6. Starting in 1969 sediment dredged from the channel as part of the maintenance dredging operation was dumped along the north side of the harbour to create wave refraction mounds. In the natural flat seabed condition waves pass up the harbour unattenuated by wave refraction effects. The shallower water over the wave refraction mounds slows that part of the wave front passing over it, turning the wave front in towards the shore and reducing the wave energy passing up the harbour.

7. The wave orthogonals, imaginary lines running perpendicular to the wave front, spread out as the wave refracts and the energy contained between them is then spread out over a wider wave front resulting in lower wave heights. The natural processes act over time to level these mounds to return the seabed to its natural flat condition.

8. The channel has its own wave refraction effect. That part of the wave front passing up the channel moves faster than the wave front sections to the side of the channel causing the wave orthogonals to bend outwards away from the channel and even to converge increasing wave heights to the side. Where there are wave peaks diffraction effects result in energy being transferred along the crest. This process has been confirmed and quantified by the MSL wave modelling work.

9. While the outer and central – opposite the port – parts of the harbour are in general quasi stability sediment accumulation has occurred in the three main bays of the upper harbour, Hart et al 2008b. The same study also suggested that pulses of sediment from catchment development may have increased in recent years.

9.2 Sedimentation in Pegasus Bay

1. The fine sediment moving north around Banks Peninsula is derived from the suspended loads delivered to the sea south of Banks Peninsula by the Rakaia, Ashburton and Rangitata Rivers. It has been estimated (R M Kirk) that the total annual transport of material past Banks Peninsula might exceed 8 million tonnes per year.

2. These sediments have the same mineralogy and behaviour in the marine environment as the loess material mantling the slopes of Banks Peninsula. These sediment particles derive from the same source, from the Torlesse Supergroup greywacke rocks in the Southern Alps. The fine sediment being transported north has been the source of the sand accumulating in Okains Bay, resulting in an average rate of shoreline advance of 3.9 m/year (R M Kirk).

3. North of the peninsula the Waimakariri River discharges the same sort of sediment into Pegasus Bay. In north east conditions this material is carried south, assisted by the flood tide current which sets south. Photograph No 19 shows the leading edge of a turbidity plume from the Waimakariri River in flood close to Godley Head. The outgoing tidal flow from Lyttelton Harbour has stalled progress south.

4. There is a wide range of estimates of the suspended sediment load for the Waimakariri River – ranging from 2.78 million tonnes per year (Benson 1946) to 5.36 million tonnes per year (Griffiths 1981). In a 1998 review of the sediment budget for Pegasus Bay Hicks suggests a true value closer to the lower end of the range. The later (2000) Kirk and Lauder estimated figure for the suspended sediment input to Pegasus Bay from the Waimakariri River is 5.4 million tonnes, the same as Griffiths. The suspended loads for the Ashley and Waipara Rivers which discharge into Pegasus Bay north of the Waimakariri Griffiths and Glasby (1985) estimated the suspended sediment loads to be respectively 1.16 and .46 million tonnes per year.

5. The depths in Pegasus Bay are stable, there has been little change in recent times, geological time scales excluded, but this is not evidence of small volumes of sediment in motion. Huge volumes of sediment will be entrained into suspension in storm events but because the seabed is essentially flat and featureless there is no evidence of this movement in the absence of sediment traps. The fine sediment material, silt and clay discharged from the river deposits in deeper water offshore forming part of the mobile ubiquitous fluid mud layer. It does not settle out close to shore near the surf zone because of the high energy seastate.

6. The trenches dredged as part of the construction of the Waimakariri and Christchurch ocean outfalls constituted sediment traps. Even in relatively calm conditions the trenches, 4 m deep for the Christchurch outfall, trapped silt in suspension in the permanent turbid layer close to the seabed reducing underwater visibility for divers working on the pipe to zero. Divers needed to carry additional weight to counter the increased buoyancy effect in the turbid water in the trench.

7. The trench for the Christchurch outfall which was completed in 2010 filled in by as much as 2 m in one storm event. The rate of infill depended on the depth at the location considered. Close to the surf zone at the end of the microtunnel in 9 m water depth the 4 m trench depth could be completely lost in one storm event. Out at the end of the outfall in 17 m water depth the rate of infill is much slower.

9.3 Channel Siltation

1. Predicting the rate of siltation in dredged channels is difficult and inexact due to the complex nature of sediment transport processes. For the case of Lyttelton however there is a long history to draw on since dredging in the channel outside the inner harbour started in 1880. The siltation in the channel is heaviest opposite the dumping grounds on the north side of the harbour although it has been found that the siltation volumes are relatively insensitive to the location of the dumping grounds.

2. Deposition of sediment from suspension occurs in areas of low bed shear stress below a critical value. The bed shear levels in the bottom of the navigation channel are lower than on the seabed either side of the channel because of the greater depth. Wave induced water particle velocities and related bed shear values drop off exponentially with depth.

3. There is a form of dynamic equilibrium in operation as a result of the lower bed shear stress levels in deeper water. This acts to cause deposition in deeper areas, filling them in and promoting a return to the naturally flat seabed characteristic of the harbour. The converse is also true, the same mechanism acts to level shallower areas where the bed shear stress levels are higher.

4. The navigation channel tends to act as a sediment trap because it is deeper than the natural bed levels. This tendency is reinforced by density differences. Sediment suspended in the seawater makes it denser relative to clean seawater and the suspended sediment sinks to the bottom of depressions in the seabed. The suspensions are still moved by tidal currents in the channel but have a natural tendency to accumulate there. Much also depends on the net movement of the tidal currents in a complete tidal cycle, whether the suspensions are swept back and forth in a balanced movement, no net progress, or whether the tidal current can move the suspended sediment completely away from the channel in one tidal cycle.

5. Deepening the channel will not change the amount of siltation experienced along the length of the existing channel it is just deepening the sediment trap. Extending the channel will extend the length of the trap. The extra volume of sediment that needs to be removed as part of the maintenance dredging will most likely be less than proportionate to the increase in channel length. Although the channel will extend out past the Heads and part of the wave filtering effect of the harbour will be lost as the wave environment comes closer to open sea conditions with more bottom disturbance the effect is ameliorated by the greater depth.

6. The tidal currents will also have a smaller cross channel component than further into the harbour where both the ebb and flood currents cross the channel seaward of the Cashin Quay breakwater. The increase in maintenance dredging volume consequent on the increase in channel length corresponding to a 4 m depth increase is estimated to be of the order of 30%.

7. The limited tidal excursion distances within the harbour dictated that any dredged material dumped inside or west of Breeze Bay and mobilised by wave action would stay in circulation in the harbour being swept back and forth by the tidal currents - with a tidal residual induced incremental, cumulative, movement towards the Heads - for as long as the sediment remains in suspension.

8. Whether the sediment stays in suspension is determined by the prevailing wave energy and the depth. In its fluid state however the sediment is readily disturbed by any significant wave action anywhere in the harbour, particularly along the dumping grounds on the north side of the harbour – latterly close to Godley Head. The tidal currents however are rarely strong enough to mobilise the sediment into suspension by themselves, they act principally to transport the sediment once suspended.

9. For dumping grounds inside the Heads much of the dumped material disturbed by wave action will be retained within the harbour - recirculated. Essentially the harbour functions as a closed system.

9.4 Sediment Trend Analysis

1. Sediment Trend Analysis (STA) is a technique that determines net sediment transport pathways and the dynamic behaviours of bottom sediments from the relative changes in grain size distributions.

2. The technique was applied in the outer harbour area of Lyttelton Harbour to establish patterns of net sediment transport and determine areas of erosion, stability (dynamic equilibrium) and deposition. In addition the technique was expected to identify sources and sinks of sediment and to generate maps of the pathways, sediment types and transport environments. A particular objective was to assess patterns of sediment transport with respect to the dispersal of dredged material and channel infilling.

3. STA is an empirical method whereby sediment distributions are used as the observations necessary to establish the net patterns of sediment transport and their dynamic behaviour. As opposed to numerical modelling which is based on assumptions STA is based on observations using the only data that has indisputably integrated all the processes responsible to move and deposit sediment – the sediments themselves.

4. Sediment grab samples (300) were collected from 20 to 24 August 2012, using OCEL's survey boat, from the outer harbour. The survey area and sample locations are shown in Figure No 23, the sample locations were on a 225 m square grid. The samples were taken from the top 100-150 mm of sediment using a Van Veen grab sampler.

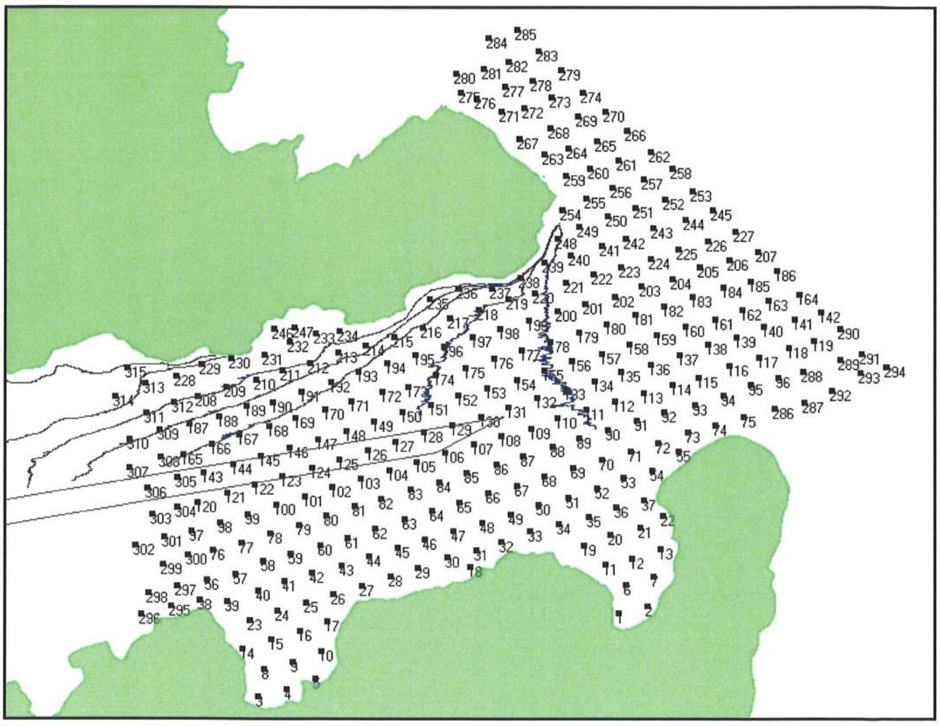


Figure No 23
Locations of the samples used in the STA. Distance between samples is 225 m

5. All the samples were subsequently analysed using a Malvern Master Sizer 200 laser particle sizer. When necessary samples containing sizes greater than 1 mm were also sieved and merged with the laser data to provide complete distributions.

6. The size analysis showed that mud (silt and clay < 63 μm) dominated the study area with decreasing amounts of sandy mud, muddy sand and sand respectively. Following the STA it was found that nearly all samples could be accounted for in 68 lines or sample sequences in which statistically acceptable trends were obtained. An exception was found in a small area near the entrance to Port Levy. The sediment types are identified in Figure No 24.

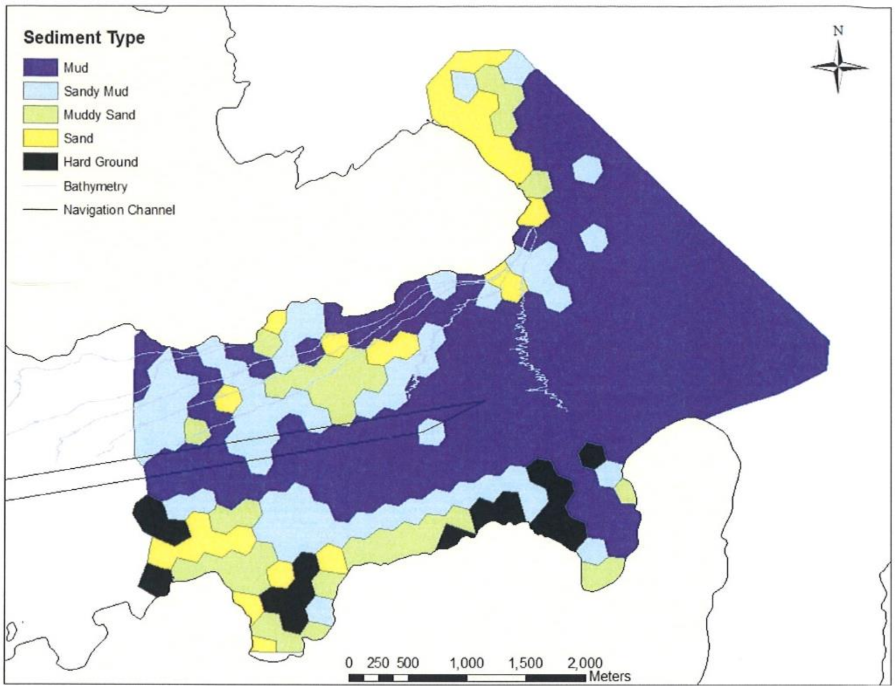


Figure No 24
Sediment types in outer Lyttelton Harbour

7. The transport lines have been grouped into two transport environments (TEs), Figure No 25. A transport environment is defined as an area containing a number of transport lines that are commonly related to each other. Transport lines cannot be continued from one TE into another so a region in which transport lines naturally end (and begin) forms a boundary between transport environments. Pathways of net sediment transport in the outer harbour are shown in Figure No 26.

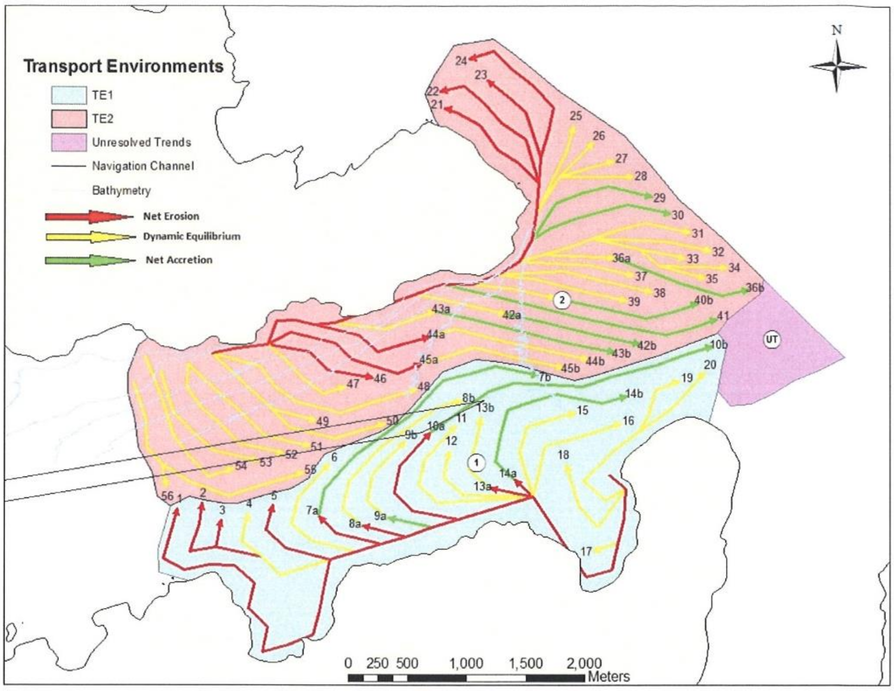


Figure No 25
Transport lines and associated Transport Environments (TEs) as determined from the STA

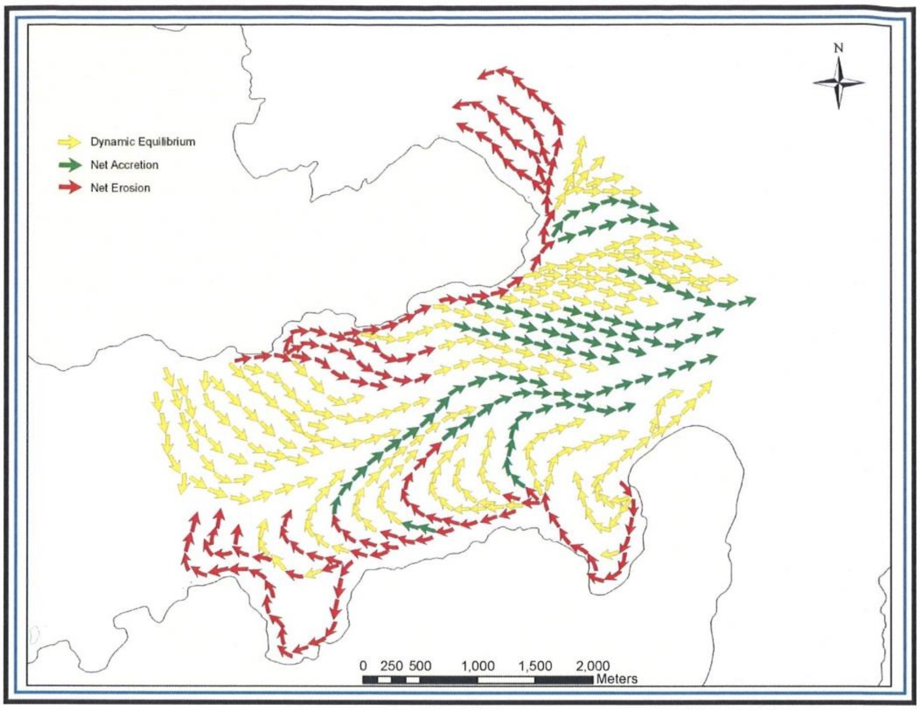


Figure No 26
Pathways of net sediment transport in outer Lyttelton Harbour

8. The STA showed that the processes of mass wasting on the steep hillsides surrounding the outer harbour supplies much of the sediment that enters the shoreline waters. Highly dynamic processes transport these sediments westward on the south side and eastwards on the north side. The material shown being transported north in the direction of Taylors Mistake is sand only.

9. At the same time finer material is driven from each side towards the middle where seaward transport continues into Pegasus Bay. In addition to the mass wasting input of sediment, material is also derived from dredged material disposed of on the north side (although the south side received dredged material prior to 43 years ago). The derived patterns of transport and the dynamic behaviours of the trends demonstrate that there is no longer any evidence for the dredged material disposed of on the south side. There is a possibility that some of this material has been driven farther westwards into the harbour (the area sampled is insufficient to assess this) but certainly it is likely that much of it has been lost to sea.

10. On the north side the dredged material is evident although it is mixed and transported with the naturally occurring sediments. Dredgate on the north side is unlikely to be transported westwards up the harbour and it too follows pathways taking it seaward into Pegasus Bay.

It was suggested that the environment on the north side could accept more sediment from dredging operations than it was presently receiving (2012). While disposal operations do locally affect erosion and deposition, most of the trends are in Dynamic Equilibrium and deposition as a result of nearby disposal operations appears to be temporary. It would, however, minimise depositional effects if disposal sites are dispersed and each one used as infrequently as possible.

The conceptual understanding provided by the STA of how the sediments and dynamics of this area of Lyttelton Harbour are behaving did not appear to conflict in any substantive way with the existing knowledge of sediment and water movement.

10.0 FLUID MUD LAYER

Dynamic penetrometers deployed either by crane or dropped from a support vessel have proven to be a time and cost effective means to profile seafloor sediment strength vertically. Two types of dynamic penetrometer, a free-fall CPT (Cone Penetration Test) lance and a smaller hand carried unit called NIMROD, both developed by MARUM, the Centre for Marine Environmental Sciences at the University of Bremen in Germany, have been used to investigate the seabed in Lyttelton Harbour and offshore at the proposed dumping location. The University of Bremen has an ongoing cooperation with the Coastal Marine Group at the University of Waikato, hence the availability of this specialist equipment in New Zealand. The NIMROD is a unique instrument that enabled detailed investigation of the fluid mud layer found both in and outside Lyttelton Harbour. Something not previously possible prior to the development of the instrument. The turbidity meter identified the increasing density of the turbid seawater close to the seabed but does not fully resolve the fluid mud layer.

10.1 NIMROD

1. The NIMROD IS a hand carried dynamic penetrometer that has been developed by MARUM to address the problem of resolving very soft to fluid mud layers. The device has a high sensitivity for low sediment resistances and has a range of different tip geometry configurations – flat cylinder, hemisphere and cone – to achieve this. A hemisphere was used for the Lyttelton work.

2. The NIMROD is deployed by throwing it overboard - reference Photograph No 25. It is a fluid dynamically shaped device with tail fins and a fall stabilising relationship between the centre of gravity (CofG) and the centre of buoyancy (CofB). The CofG is below the CofB. This ensures that whatever the initial orientation on entering the water the NIMROD impacts the seabed vertically.

Photograph No 25

3. NIMROD impacts the seabed at the terminal velocity it reached during its fall through the water column and is then decelerated depending on the sediment properties, the properties of the probe itself and its

free-fall behaviour. The device is equipped with four accelerometers with different ranges and resolutions. Layers of different strength and density can be distinguished from each other using the deceleration-depth profiles.

4. The seabed impact signature in the form of a deceleration-depth profile is recorded onboard and later downloaded and processed to derive the quasi-static bearing capacity using a strain rate factor. This transforms the dynamic sediment resistance to a quasi-static sediment resistance that relates to penetration with constant velocity v_o = .02 m/sec. Dividing the quasi-static sediment resistance by the cross section area of the NIMROD gives the quasi-static bearing capacity (qsbc).

5. The survey work undertaken at Lyttelton with the NIMROD was classified in to three areas – the dredged channel, the existing dredged material disposal grounds on the north side of the harbour and the proposed offshore disposal site.

6. In the dredged channel the seabed was pre-dominantly characterised by a two layer system of a very soft top layer, qsbc < 1 kPa, over a stiffer substratum. The top layer showed a thickness ranging from 5 – 8 cm +/-1 cm inside the harbour increasing to 10 – 17 cm thick at the harbour entrance. The soft top layer in the channel was thickest, 45 cm, +/- 1 cm, and 20 cm, +/- 1 cm, opposite the disposal grounds on the north side of the harbour.

7. The substratum had a qsbc ranging from 5 – 9 kPa +/- 2 kPa with maximum penetration depths ranging from 32 – 60 cm +/- 1 cm. Closer to the port the top of the hard layer in the channel was picked up.

8. On the northern flank of the harbour the soft top layer was present but the second layer sediment appeared predominantly softer, 2 – 5 kPa +/-1 kPa. The maximum penetration depth ranged from 39 – 88 cm +/- 1 cm.. This confirms the low consolidation rate of the dumped dredged material on the north side of the harbour. A hard bottom was identified off the shoreline at Te Awaparahi Bay.

9. The NIMROD results for the proposed disposal site offshore showed a natural soft top layer similar to that in the dredged channel but not as thick as at the harbour entrance. The qsbc value for the substratum ranged from 9 – 10 kPa +/- 3 kPa. The maximum penetration depth was 24 cm +/- 1 cm.

10. As for the mobile ADCP current studies the dynamic penetrometer results represent a snap shot in time but clearly identify the persistent, natural, highly mobile fluid layer on top of the seabed.

11. Representative graphical results of the NIMROD results are given in Figure Nos 27 (position 24), 28 (position 71) and 29 (position 63) for the three survey areas. The locations of both the FF-CPT and the NIMROD test positions are shown on Drawing No DR-030901-026.

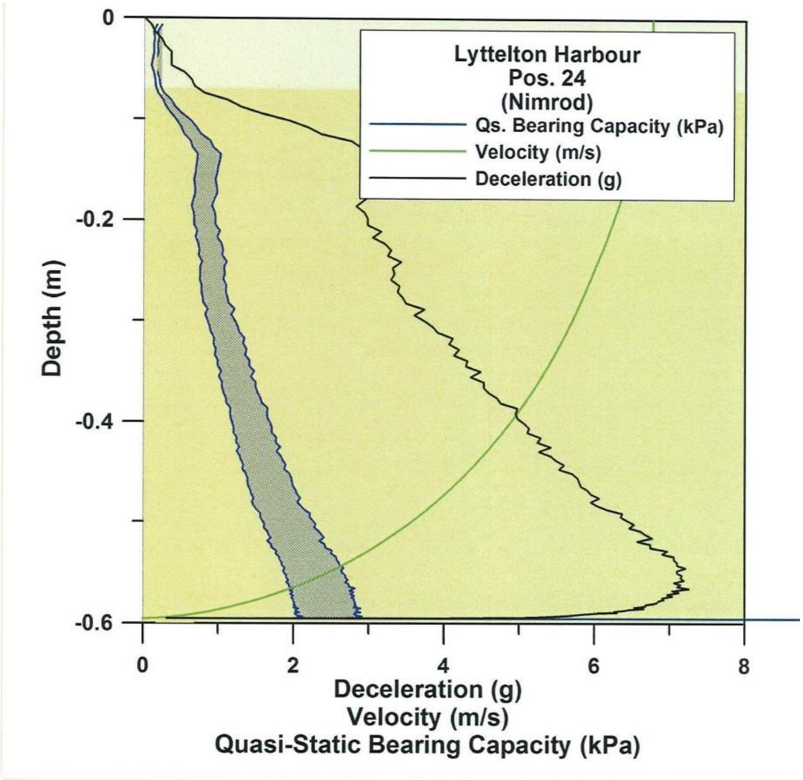


Figure No 27

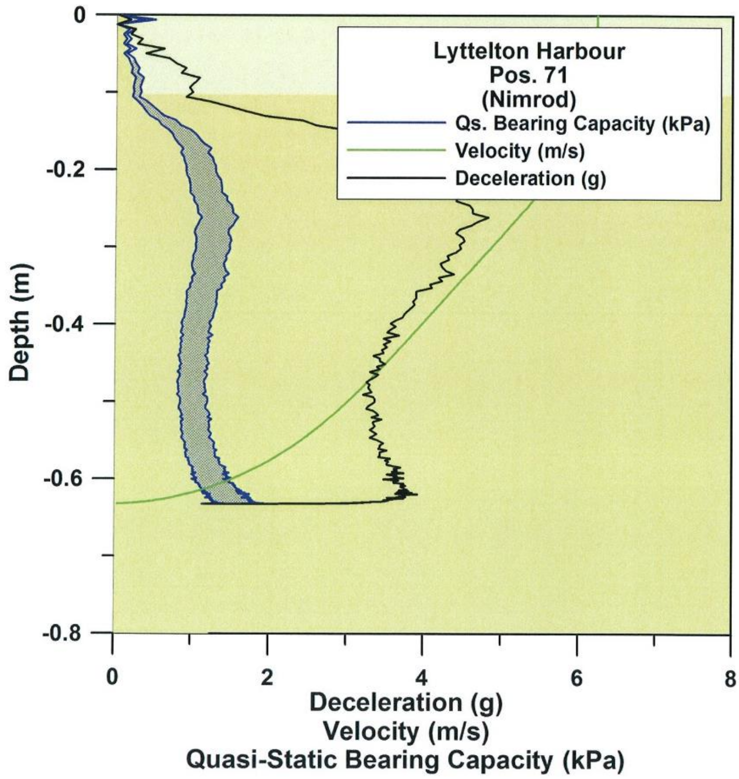


Figure No 28

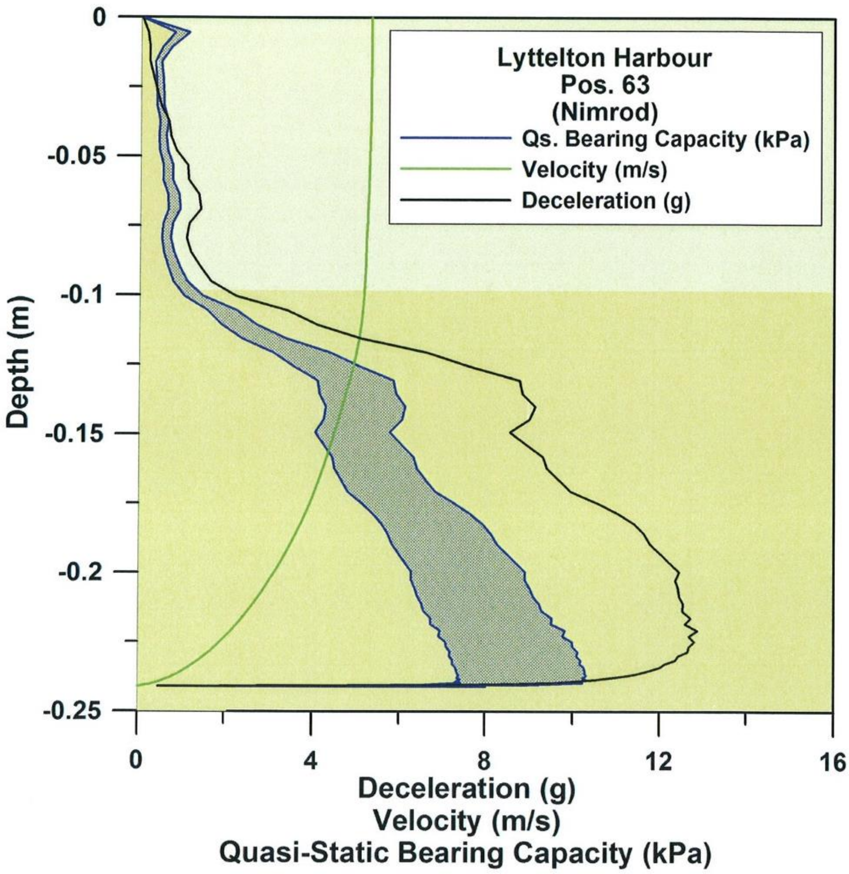


Figure No 29

10.2 FFCPT

1. The Free Fall Cone Penetrometer provides the same soil information as the conventional CPT device but corrections are required to allow for the greater, and variable, speed of penetration for the Free-Fall CPT (FF CPT). For a conventional CPT the cone is advanced at a set rate of advance (.02 m/sec) by a hydraulic ram. The FF-CPT has a penetration rate which decreases during the penetration process. This leads to a variable strain dependency of the sediment strength reflecting properties such as deceleration, tip resistance or sleeve friction.

2. Strain rate factors are available from soil mechanics research references (eg Stoll et al 2007 – Seafloor Properties from Penetrometer Tests) to convert quasi-static sediment resistance to higher dynamic penetration rates and vice versa when the deceleration-depth profile, and hence the decreasing velocity of penetration, is known.

3. The cones used are piezo-electric cones that allow measurement of the pore water pressure in the soil. Pore pressures rise during impact but decay toward ambient values at a rate dependent on the soil type.

4. The FF-CPT incorporates an accelerometer which provides information about the descent velocities and deceleration behaviour of the instrument on penetration. The penetration depth is determined by integration of the deceleration-depth profile record.

5. The FF-CPT was deployed using a winch line from the stern A-frame of the support vessel 'Soundz Image', reference Photograph No 13. The length of the CPT lance can be increased in 1 m increments from the starting point 1,5 m and the weight of the unit can be increased to assist penetration by adding 15 kg weights.

6. A total of 15 deployments were carried out inside the harbour to gather data on the strength of the seabed sediment, derived from the resistance of the cone and the sleeve of the probe during penetration, and to classify the sediment based on the friction ratio (sleeve friction/cone resistance) corrected for pore pressure effects. The maximum penetration achieved was 4 m. Representative results for the FF-CPT – respectively for the existing channel, position 9 and the proposed channel extension, positions 38 and 62 - are shown in Figure Nos 30, 31 and 32. Drawing No DR-030901-026 gives the FFCPT position number plots.

8. The data gathered using the FF-CPT has complemented and extended the existing database and understanding of seabed sediment strength parameters, and their spatial distribution, for the harbour. The FF-CPT does not however pick up the presence of the very soft to fluid, highly mobile, mud layers overlaying the stiffer seabed material in Lyttelton Harbour because of the very subtle difference in the resistance of such layers compared to that of the water column.

9. The turbidity meter identifies the increasing density of the turbid seawater close to the seabed but does not fully resolve the fluid mud layer.

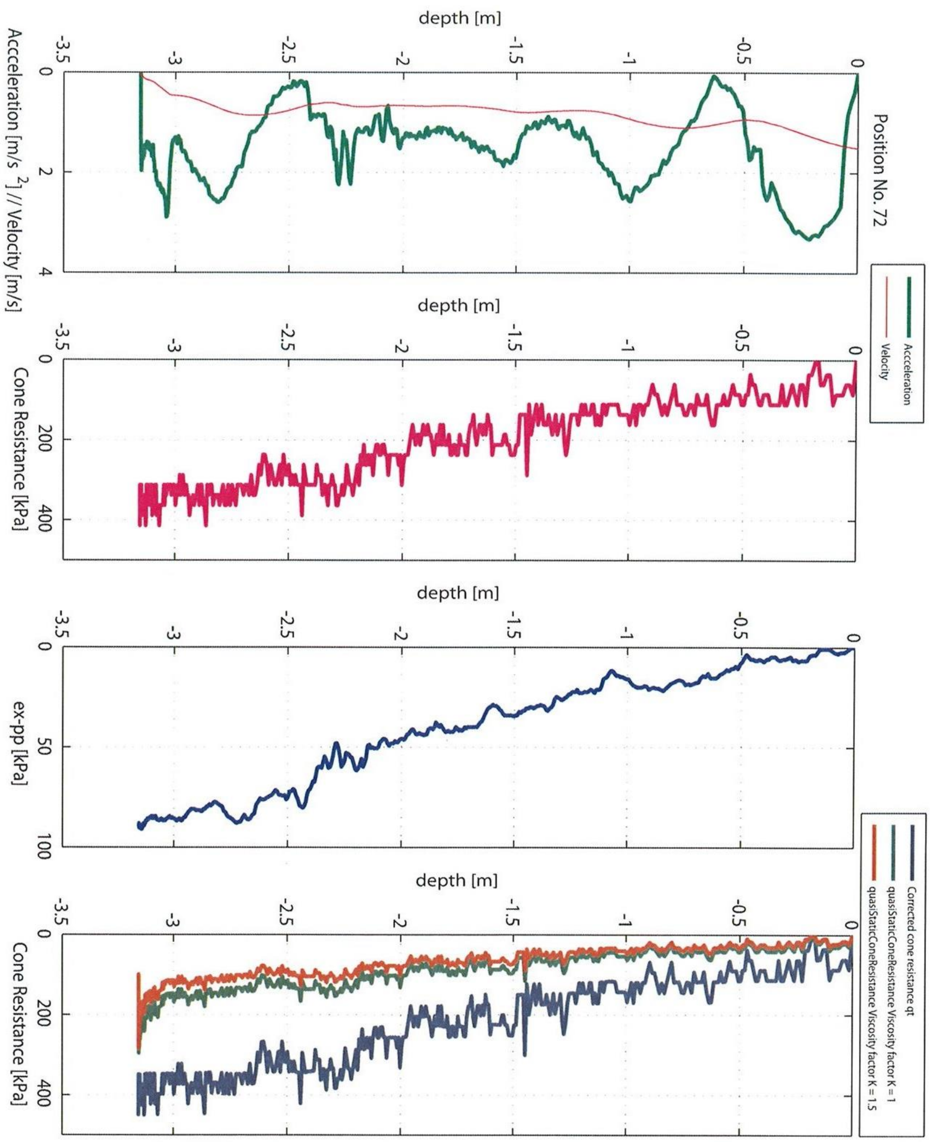


Figure No 30

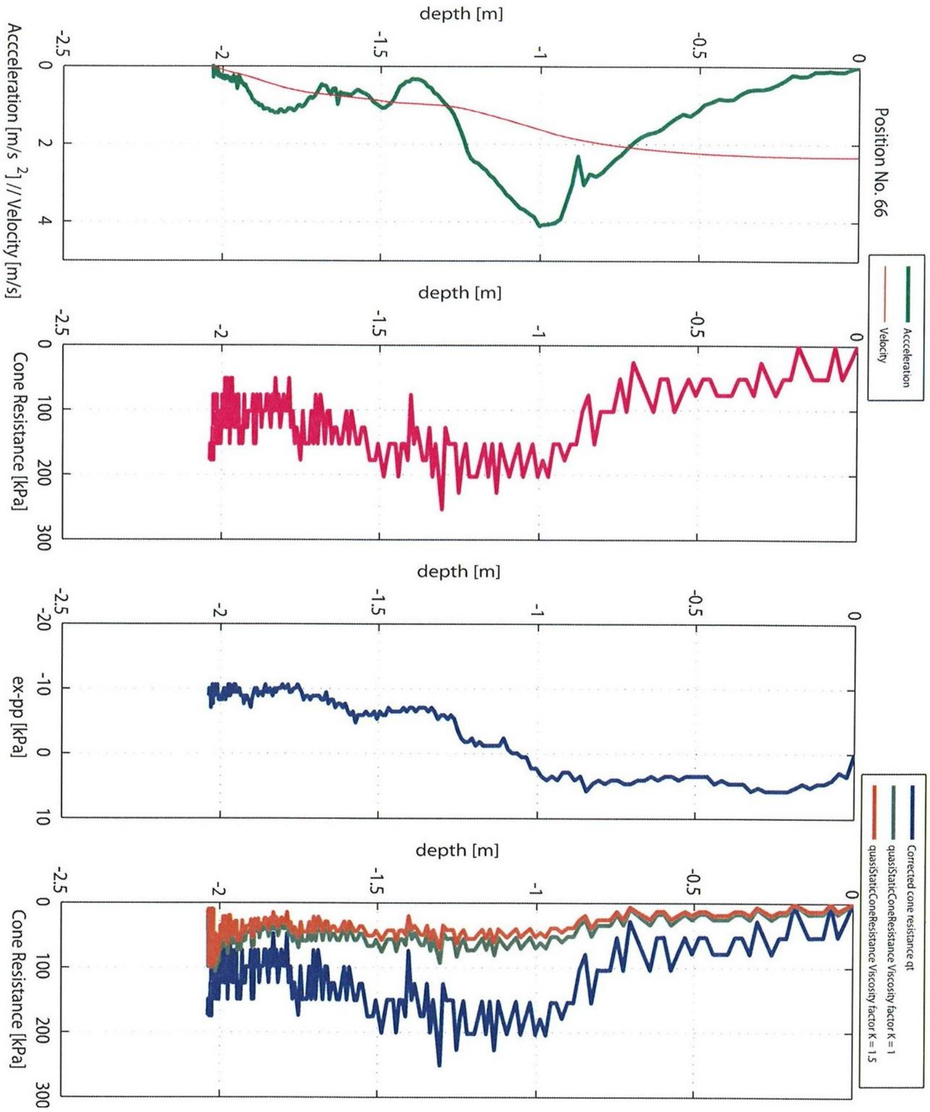

Position No. 66
depth [m]
Acceleration [m/s 2] // Velocity [m/s]
Acceleration
Velocity
Cone Resistance [kPa]
ex-pp [kPa]
Corrected cone resistance qt
quasiStaticConeResistance Viscosity factor K = 1
quasiStaticConeResistance Viscosity factor K = 1.5

Figure No 31

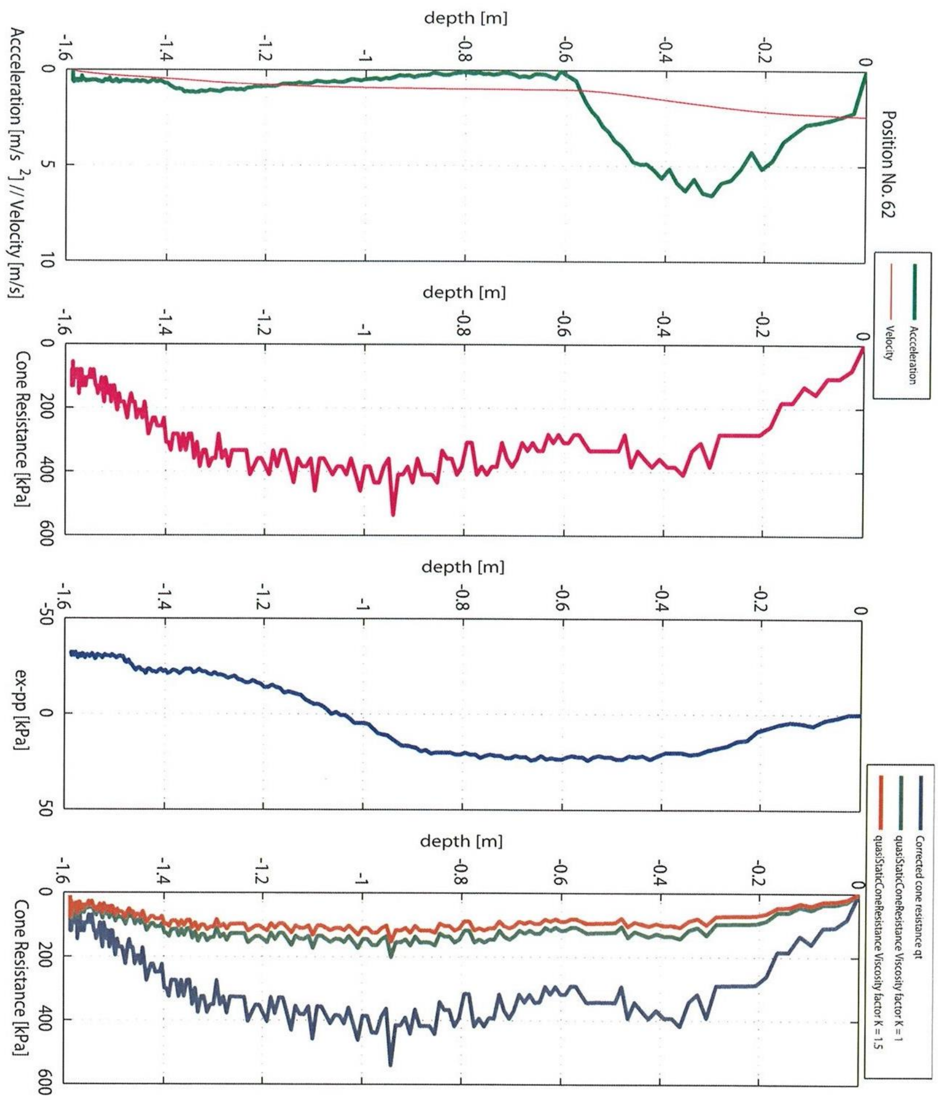

Position No. 62
depth [m]
Accceleration [m/s 2] // Velocity [m/s]
Accceleration
Velocity
Cone Resistance [kPa]
ex-pp [kPa]
Corrected cone resistance qt
quasiStaticConeResistance Viscosity factor K = 1
quasiStaticConeResistance Viscosity factor K = 1.5

Figure No 32

11.0 ENVIRONMENTAL EFFECTS OF DUMPING OFFSHORE

1. The environmental impact of dumping the material dredged as part of the CDP on the offshore area will not be high or prolonged. The turbidity generated by the dumping of the sediment will be high initially but will rapidly decay to ambient levels as was shown by the dumping trials at the offshore location and the trials were undertaken in close to calm sea conditions.

2. If there is a swell running at the time the turbidity generated by the dump will be indistinguishable from the natural turbidity produced by the swell action. The dumped material will blend into the background. The bulk of the turbid water will in any event be close to the seabed and out of public view.

3. The environment is used to high turbidity it is just that higher than normal or sustained turbidity will persist at the dump site for the duration of the CDP. The process of dispersion after the initial dispersion resulting from the descent of the material as a dense fluid to the bottom has taken place will start immediately, at a rate determined by the occurrence of swell action. Once mobilised into suspension the suspended material can be moved by the tidal currents.

4. As determined by the current survey work these tidal currents are weak and generally aligned with the coast. The material will move back and forwards parallel to the coast with the tide, the sediment being dropping out of suspension over a very large area.

5. Shallowing will be limited provided the sediment is dumped over the full extent of the dump area. Even if it was not dumped evenly any pronounced shallowing would result in higher wave induced water particle velocity and a natural levelling process will be in action.

6. The direction of the residual currents, most likely the contribution from the gyre in the lee of Banks Peninsula produced by the Southland current, will act to take the sediment south east, parallel to the line of the coast. The currents will act as a dispersion mechanism to distribute the sediment over the southern end of Pegasus Bay. The sediment will ultimately become an indistinguishable part of the natural environment in Pegasus Bay.

7. The total CDP input while amounting to several years worth of maintenance dredging will be of the order of the total volume of sediment entering Pegasus Bay, directly from the Canterbury rivers and indirectly via transport past the end of Banks Peninsula.

11.1 Effect on Port Levy and Banks Peninsula Bays

1. There is no direct tidal current path to take the dumped, re-suspended sediment into the bays of Banks Peninsula, in particular the two inlets closest to Lyttelton Harbour, Port Levy and Taylors Mistake. These inlets are relatively small inlets and do not as a consequence feature strong tidal flows either in or out. Drogues dropped along the centreline of the proposed channel extension on both the incoming and outgoing tides and moved directly in and out of Lyttelton Harbour and showed no tendency to go anywhere near Port Levy or Taylors Mistake.

2. The main tidal flows into and out of the much larger Lyttelton Harbour inlet develop weak tidal jets around the harbour entrance Heads. The jets separate from the headlands and are directed at an angle to the coast. The circulation in the adjacent bays is dominated by weak tidal gyres as the jets entrain flow in the stagnant tidal areas on the bay sides of the flow for both the incoming and outgoing tides.

3. The prevailing easterly winds will tend to move the surface water inshore but this is not of much significance because the bulk of the turbidity generated by the suspended sediment is closer to the seabed. Any water moved shorewards at the surface by local winds will be counterbalanced by an equal flow offshore. The wind has only a minor influence on the tidal current directions, as confirmed by the current drogue results.

4. Sand is known to be accumulating further east at Okains Bay from the supply of sand passing around the end of the peninsula. Waves can act to move sand shoreward as bed load the onshore velocity being higher under the crest than velocity offshore under the trough as the waves steepen in shallow water. There is no prospect of the very fine sediment building up offshore Taylors Mistake. Silt size material cannot remain in a surf zone or even close to it as the waves steepen. The natural repository for the fine material is further offshore in deep water.

12.0 CONCLUSION

1. This report presents the results of the empirical data collection work that OCEL has undertaken over the last 20 years as part of studies on the harbour tidal regime, wave environment, seabed geotechnics and vessel handling/motion studies. It has also drawn on earlier work and studies to establish a historical context. It is primarily based on observations and complements the more recent numerical modelling work by MSL.

2. The latter is based on starting assumptions which have to be subsequently validated by observations some of which has been provided by OCEL. The MSL models of tidal currents and wave energy have been tuned as a result of observations and now fully replicate measured currents and waves for the existing harbour configuration. This has provided the confidence to use the models to accurately forecast the effects of changes to the harbour configuration.

3. The wave and tidal current models have built on and extended the empirical work providing another level of detail. This has generally been the case for the different technologies (ADCP, NIMROD turbidity meters) and techniques adopted/employed on harbour investigation work over the years, they have all built on and extended the empirical work, the numerical modelling is no different.

4. The MSL model of sediment transport has not yet achieved the same validated status as the wave and tidal current models, it is a work in progress, but it is providing excellent insights into the processes of sediment entrainment and movement. One insight has been the role of waves in sediment transport. The waves have long been recognised as the principal determinant of sediment movement by stirring up the seabed and entraining sediment into suspension to be moved subsequently by tidal currents. The latest MSL work has indicated that the episodic high energy wave events may move large volumes of sediments in one event through the combination of wave mass transport and tidal currents.

5. The influence of wave mass transport is reflected in the MSL deposition footprint of dredged material dumped at the proposed new offshore dump site for the CDP material. The MSL work shows the footprint skewed to the west the previous work by OCEL and Mulgor shows it skewed to the south east as a result of residual tidal currents to the south east.

6. The difference is not of major significance, since in either interpretation the dumped material does not reach the shore and stays offshore. The difference between the empirical and the numerical modelling approaches is more significant for the case of the existing, consented maintenance dredging dump location at Godley Head. While material dumped at this location will be recirculated in the harbour a significant proportion will escape the harbour. The location was determined as the best place to dump dredged material within the Heads based in part on the dredging economics of the small maintenance dredges employed to date for the work. The choice of location was backed by empirical observations, including the use of Sediment Trend Analysis.

7. The latest MSL modelling work on the maintenance dredging has identified sediment transport pathways into the harbour from the Godley Head location. The morphology model is modelling a very complex process and has yet to be validated. Given that the LPC is currently looking for an offshore dumping location for the maintenance dredged material to avoid any recirculation and a new larger maintenance dredge will be employed, the difference between the empirical and the modelling approach will be mainly academic.

8. The empirical and the numerical modelling approaches are symbiotic in that the end point is not only to understand how the present is working but to produce full validated and quantitative predictions. The work to date has enabled a close to complete understanding of the harbour and coastal environment. Development of the numerical modelling in combination with additional data gathering to validate the model will close out the significance of wave mass transport effects.

9. Based on the empirical and modelling approaches the proposed dump location is a suitable location for the disposal of both the initial CDP material and the subsequent maintenance dredging material from the outer channel, in that the environmental impact will be minimal, the extra turbidity created by the dumping of the sediment will be masked by the existing natural background, much as the turbidity created by the test dumping was found to be indistinguishable from the natural levels at the time.

10. The principal determinant of sediment mobility is swell action. The 20 m water depth at the location of the proposed offshore dump location means that the long period swell, 10-12 seconds, has less potential for disturbing the seabed and entraining sediment at the dump site than in the shallow water in, and just outside, the Lyttelton Harbour inlet.

11. Once entrained by swell action the suspended sediment is then available to be moved by tidal currents with the level of contribution from wave mass transport yet to be quantified. The tidal currents at the proposed dump location are weak, less than 0.5 knots, and the directions are along the line of, parallel to, the coast. The most notable feature of the residual current record were relatively large, close to equal strength to the tidal currents, south easterly current events that lasted for a day or so. These currents which are probably due to back eddies in the southland current assist in the dispersion of the dumped material.

12. The dumped material will be dispersed offshore along the coast. There is no direct tidal current path to take the dumped re-suspended sediment into either Port Levy or Taylors Mistake or any of the other Banks Peninsula inlets. The total CDP input, while amounting to many years worth of maintenance dredging will be of the order of the total volume of mineralogically identical sediment entering Pegasus Bay directly from Canterbury rivers and indirectly via transport past the end of Banks Peninsula.

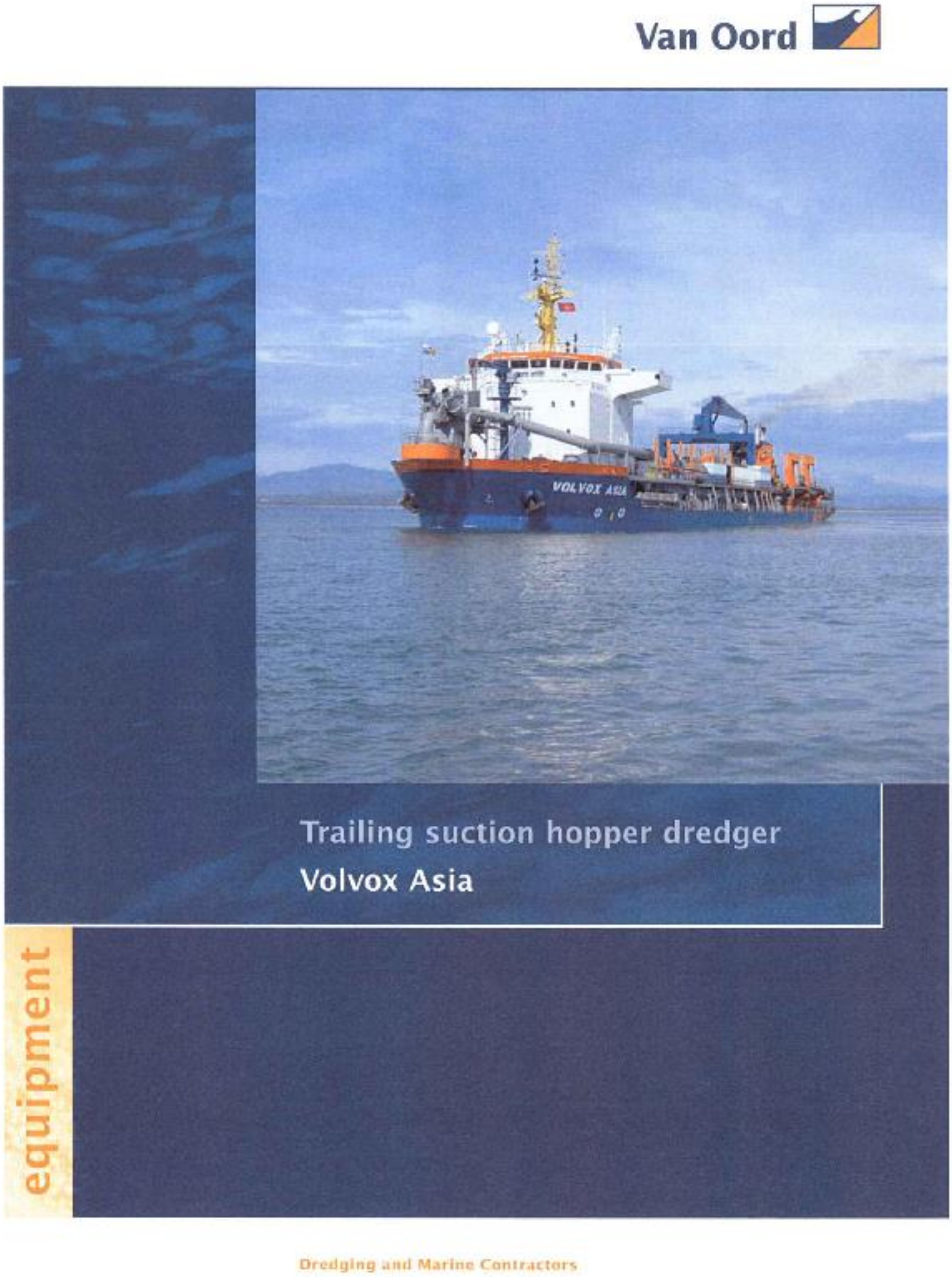
REFERENCES

APPENDIX A

DRAWINGS

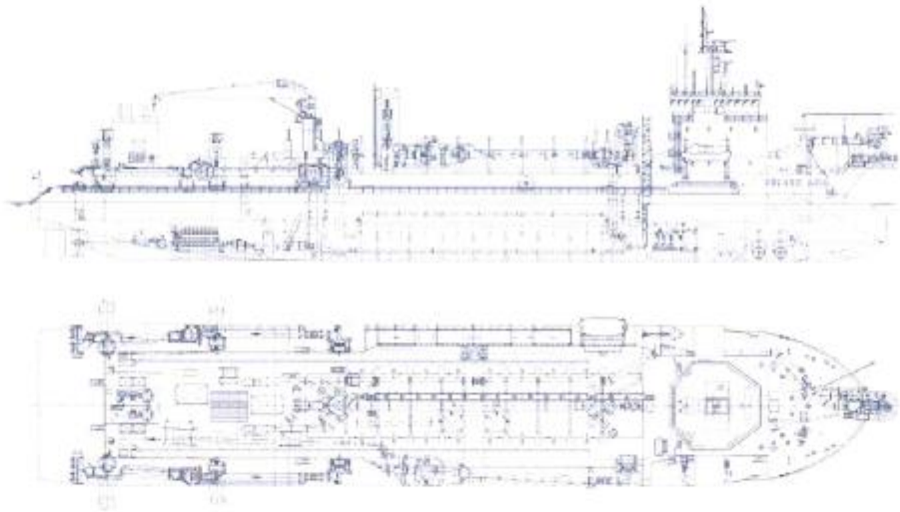
APPENDIX B

DREDGE


Van Oord
Trailing suction hopper dredger
Volvox Asia
equipment
Dredging and Marine Contractors

Principal particulars

Van Oord



Volvox Asia

Name	Volvox Asia
Type	Trailing suction hopper dredger
Classification	Bureau Veritas, I ✠ Hull ✠ Mach ✠ AUT-UMS, MON-SHAFT - hopper dredger, unrestricted navigation Dredging within 15 miles from shore or within 20 miles from port. Dredging over 15 miles from shore with H.S. ≤ 3.0 m
Year of construction	1990
Year of upgrading	2005/2007
Dimensions	Length overall 140.83 m Breadth 26.04 m Moulded depth 11.00 m Dredging draught 9.47 m
Hopper capacity	10,834 m³
Deadweight	18,064 metric tons
Maximum dredging depth	70 m
Suction pipes	2 x ø 1,100 mm & 1 x 1,100 mm/1,000 mm
Discharge pipe	ø 900 mm
Speed loaded	16 kn
Propulsion	12,120 kW
Bow thrusters	2 x 850 kW
Total power installed	21,453 kW
Dredge pump drive	2 x 2,215 kW
Submerged dredge pump	3,977 kW

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Correct at April 2008

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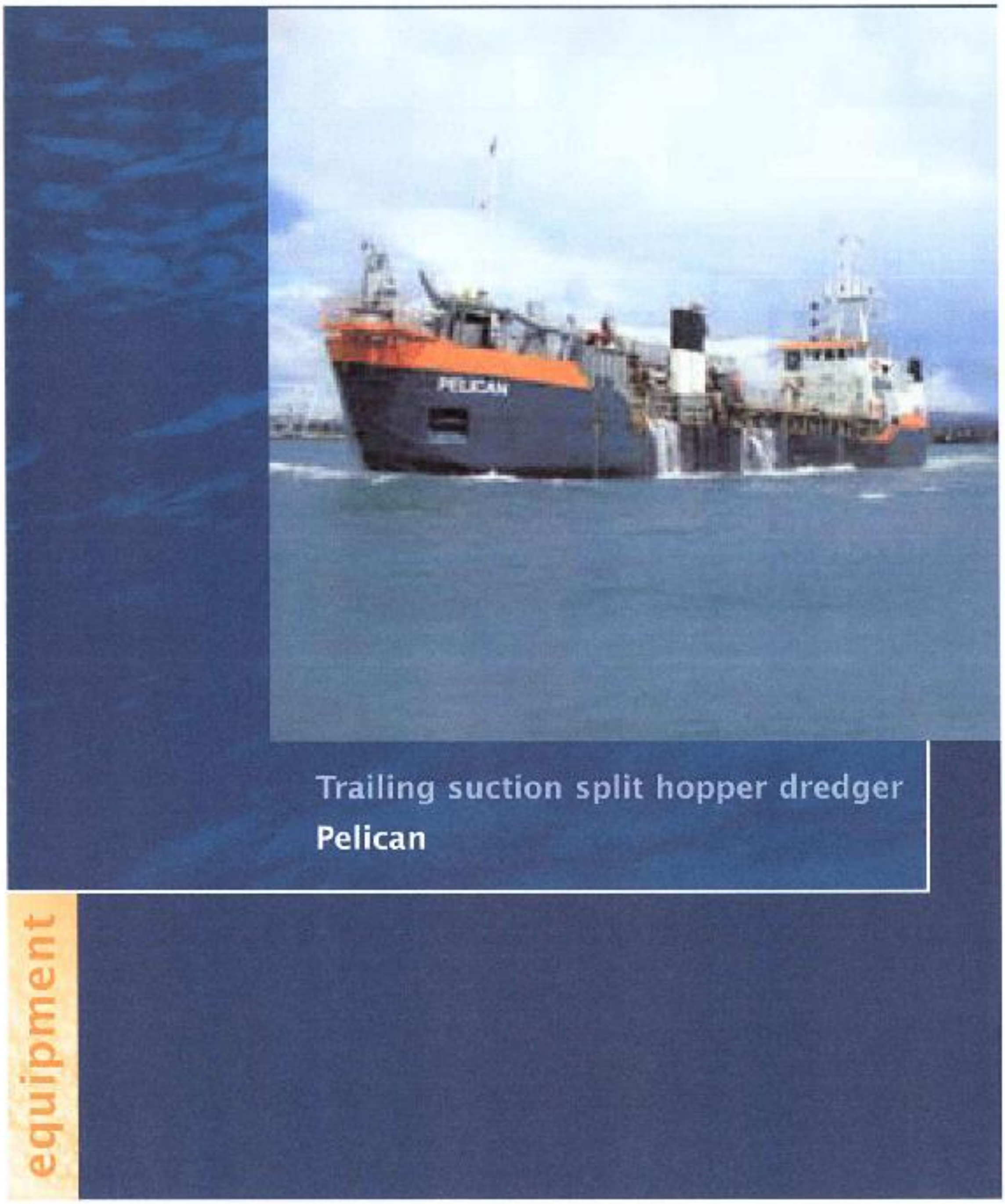
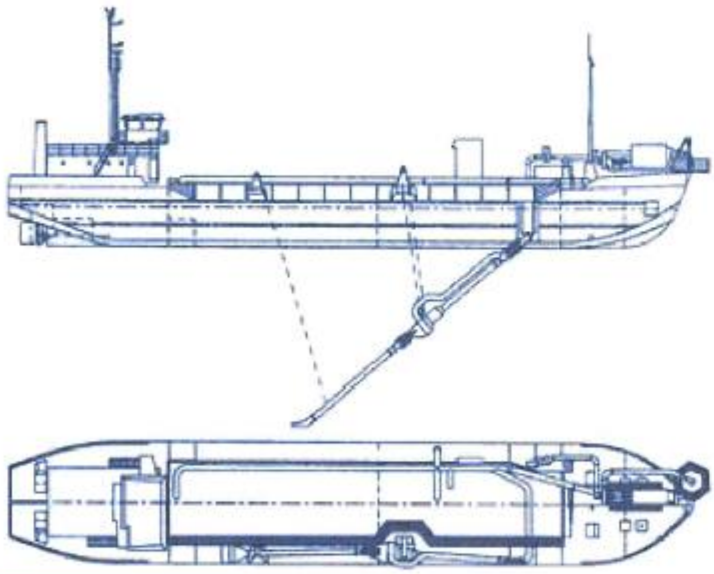


Dredging and Marine Contractors

Principal particulars

Van Oord



Pelican

Name	Pelican	
Type	Trailing suction split hopper dredger	
Classification	Bureau Veritas I, ✠ Hull, ✠ Mach, hopper dredger, unrestricted navigation	
Year of construction	1979	
Year of upgrading	1984	
Dimensions	Length overall	62.62 m
	Breadth	11.28 m
	Moulded depth	4.27 m
	Dredging draught	3.70 m
Hopper capacity	965 m^3	
Deadweight	1,376 tons	
Maximum dredging depth	20 m	
Suction pipe	ø 450 mm	
Discharge pipe	ø 450 mm	
Speed loaded	9 kn	
Propulsion	2 x 331 kW	
Bow thruster	299 kW	
Total power installed	1,811 kW	
Electric pump drive trailing	294 kW	
Discharge dredge pump	375 kW	
Jet pumps drive	1 x 201 kW, 1 x 297 kW	

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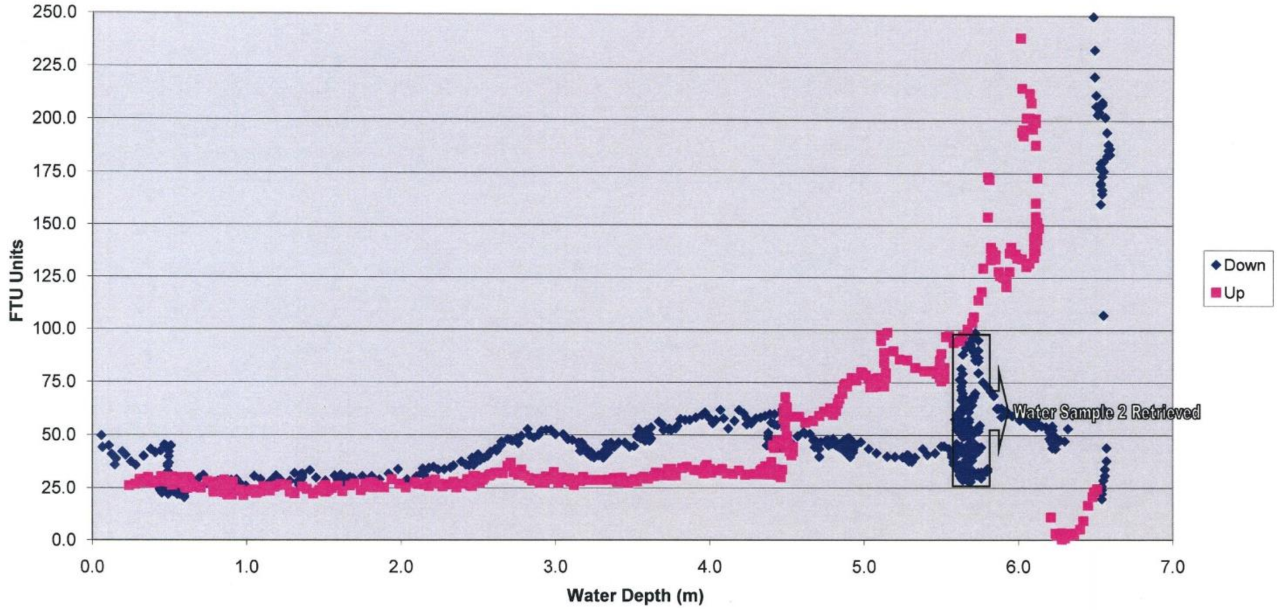
Correct at February 2005

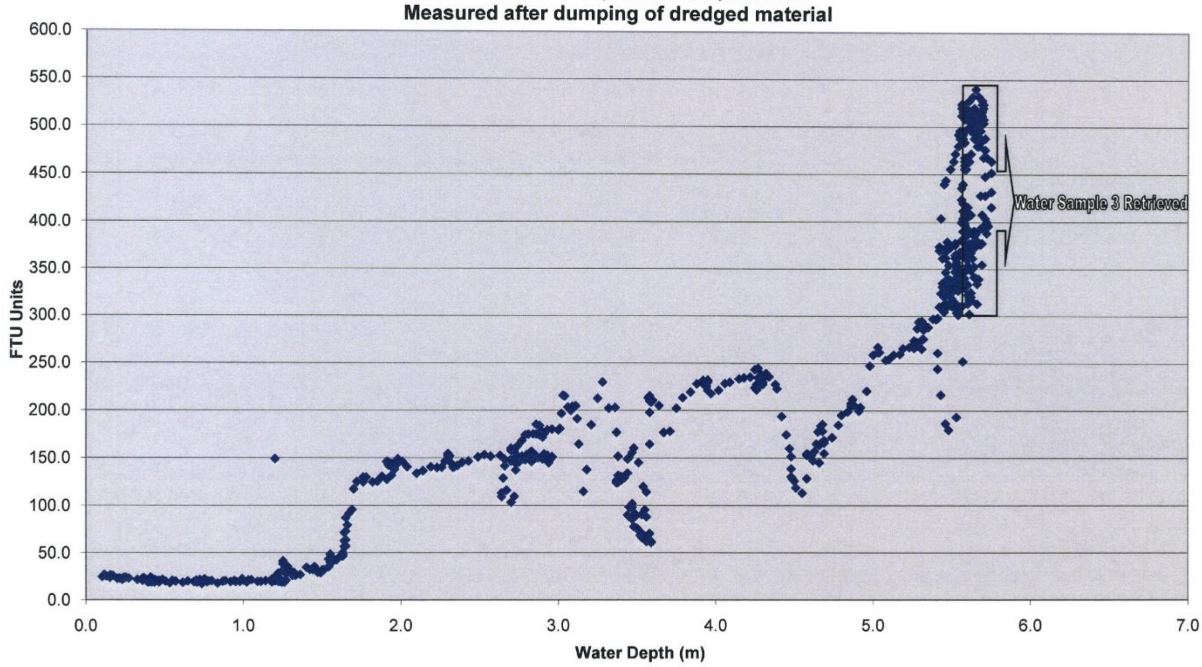
APPENDIX C

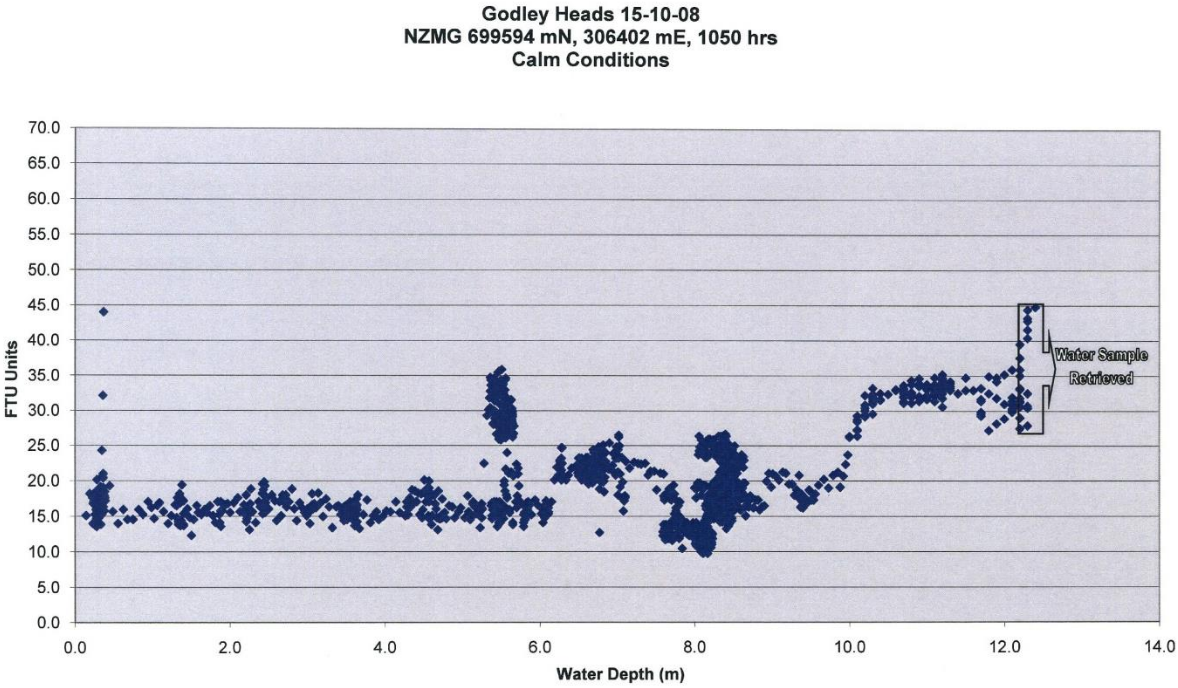
NEPHELOMETER RESULTS

Gollans Bay 15-10-08
NZMG 698603 mN, 301994 mE, 1005hrs
Measured after dumping of dredged material

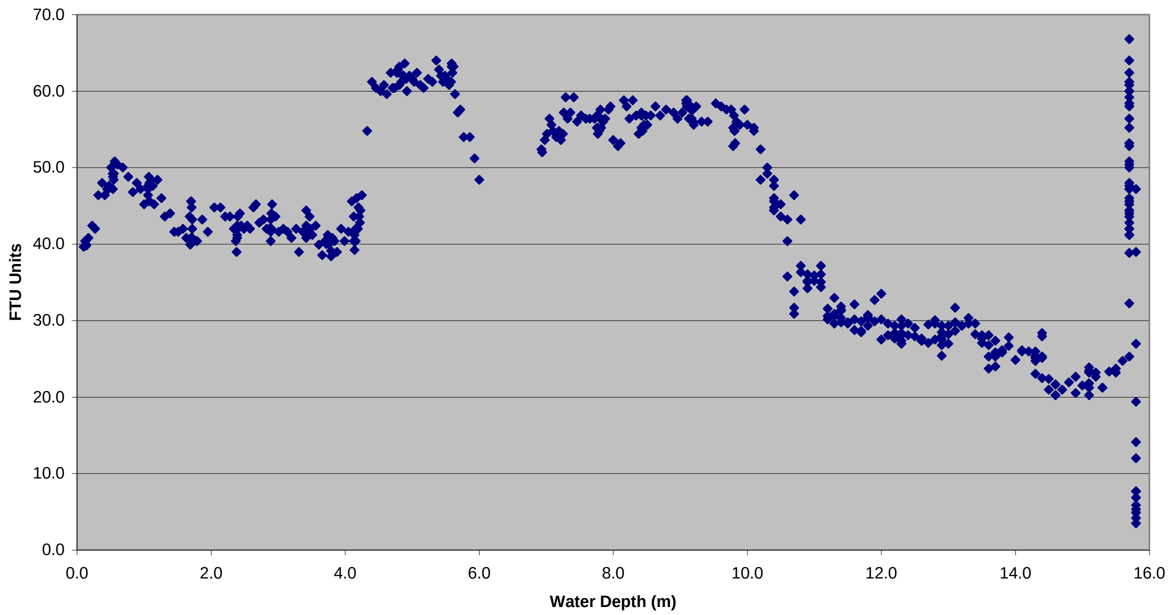


Gollans Bay 15-10-08
NZMG 698603 mN, 301994 mE, 1032hrs
Measured after dumping of dredged material

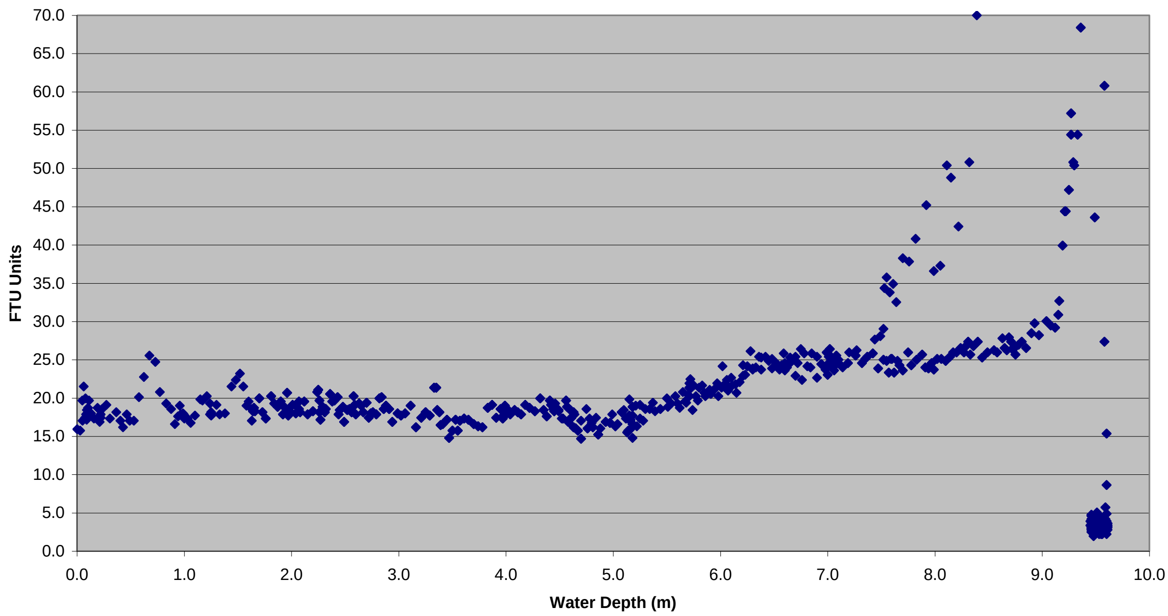


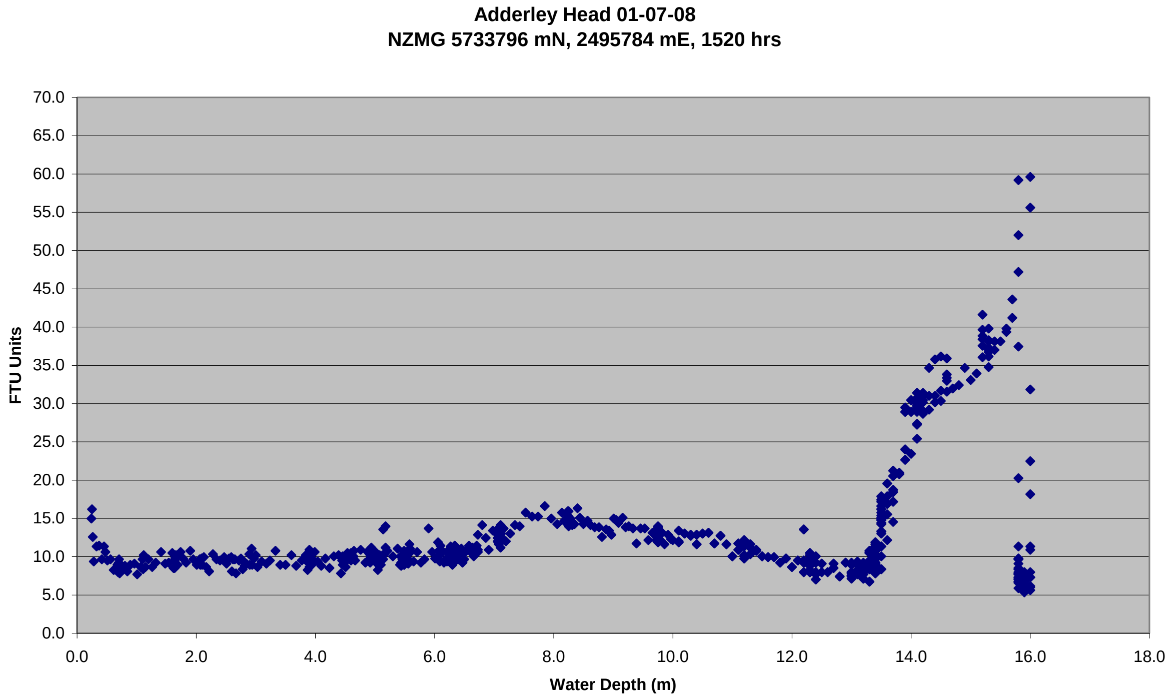

Godley Heads 15-10-08
NZMG 699594 mN, 306402 mE, 1050 hrs
Calm Conditions
FTU Units
Water Depth (m)
Water Sample Retrieved
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0

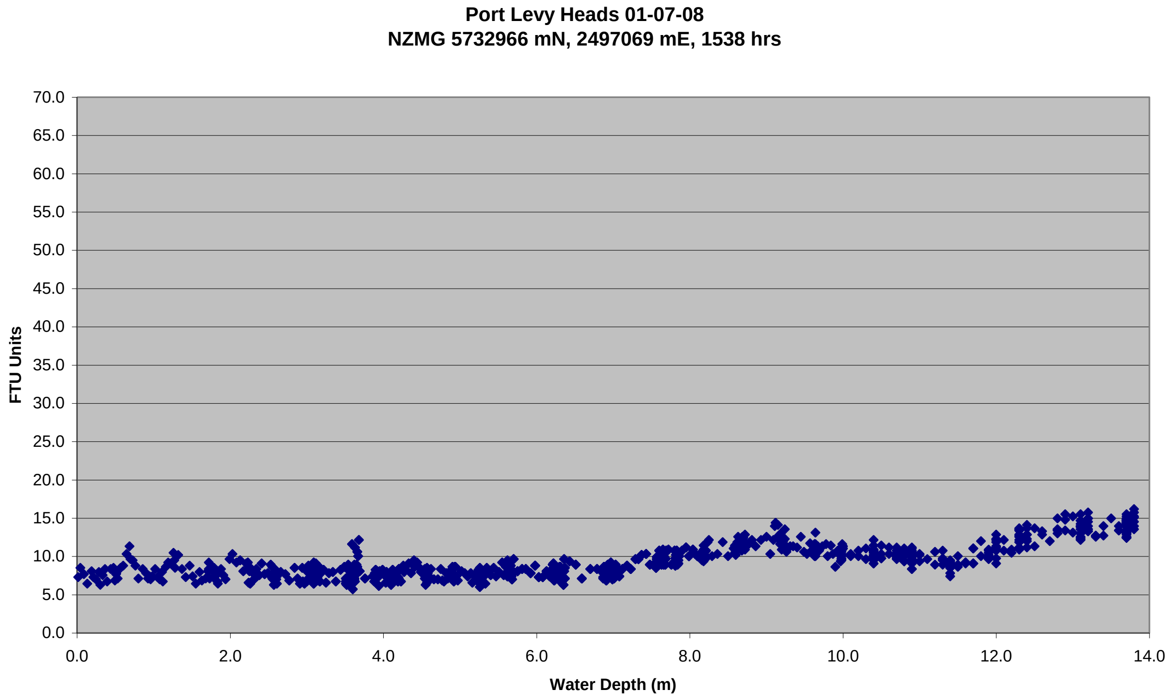
Lyttelton Harbour Channel 01-07-08 after shipping movement
NZMG 5732687 mN, 2488493 mE, 1445 hrs



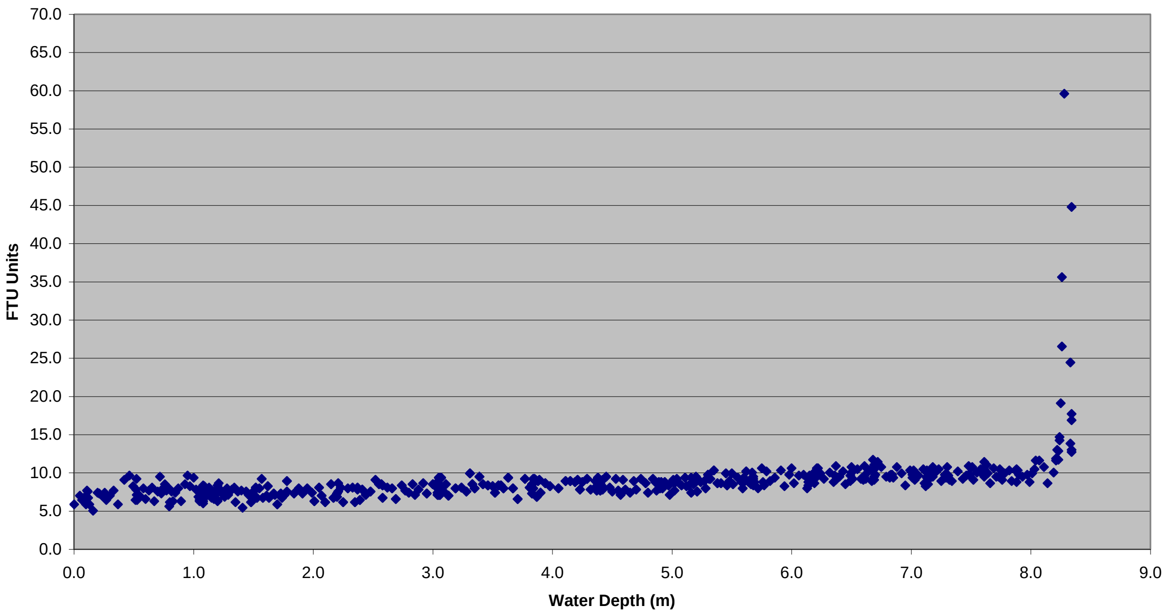
Gollans Bay 01-07-08
NZMG 5733507 mN, 2489448 mE, 1557 hrs



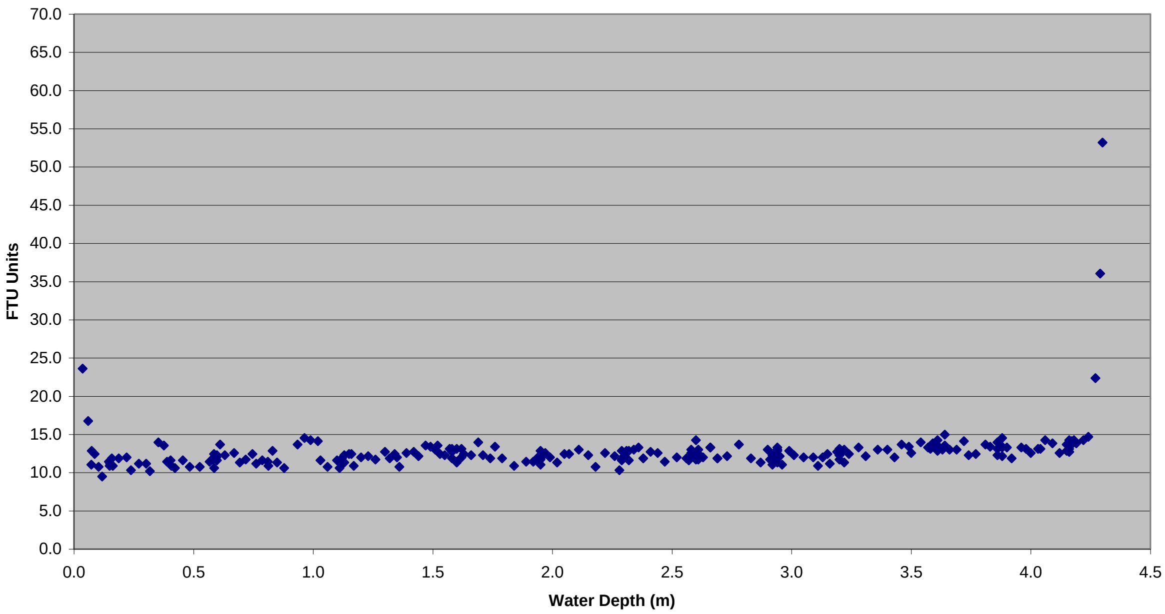

Adderley Head 01-07-08
NZMG 5733796 mN, 2495784 mE, 1520 hrs
FTU Units
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
Water Depth (m)

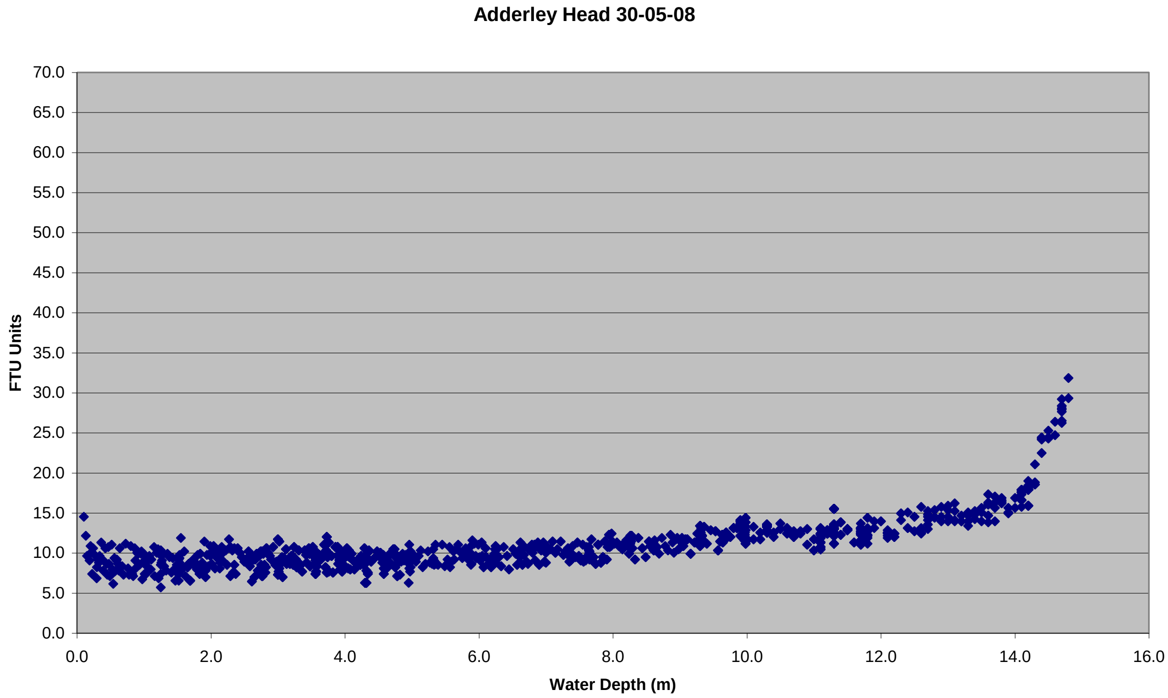

Port Levy Heads 01-07-08
NZMG 5732966 mN, 2497069 mE, 1538 hrs
FTU Units
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
Water Depth (m)

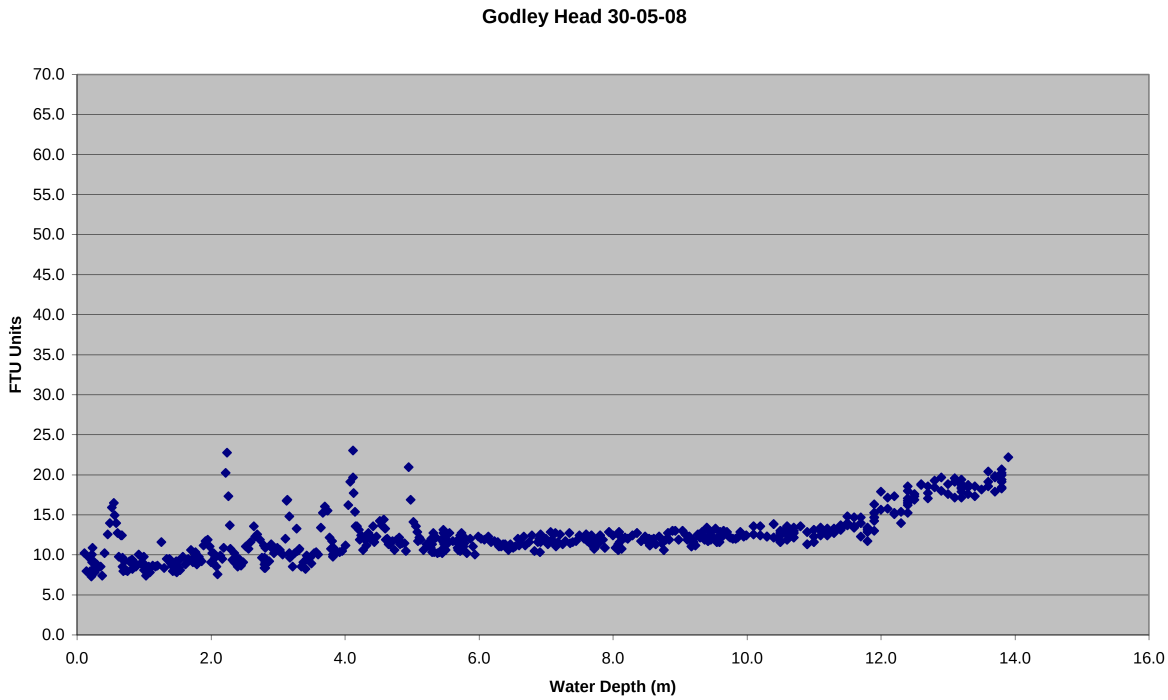
Port Levy 01-07-08
NZMG 5730609 mN, 2496180 mE, 1529 hrs

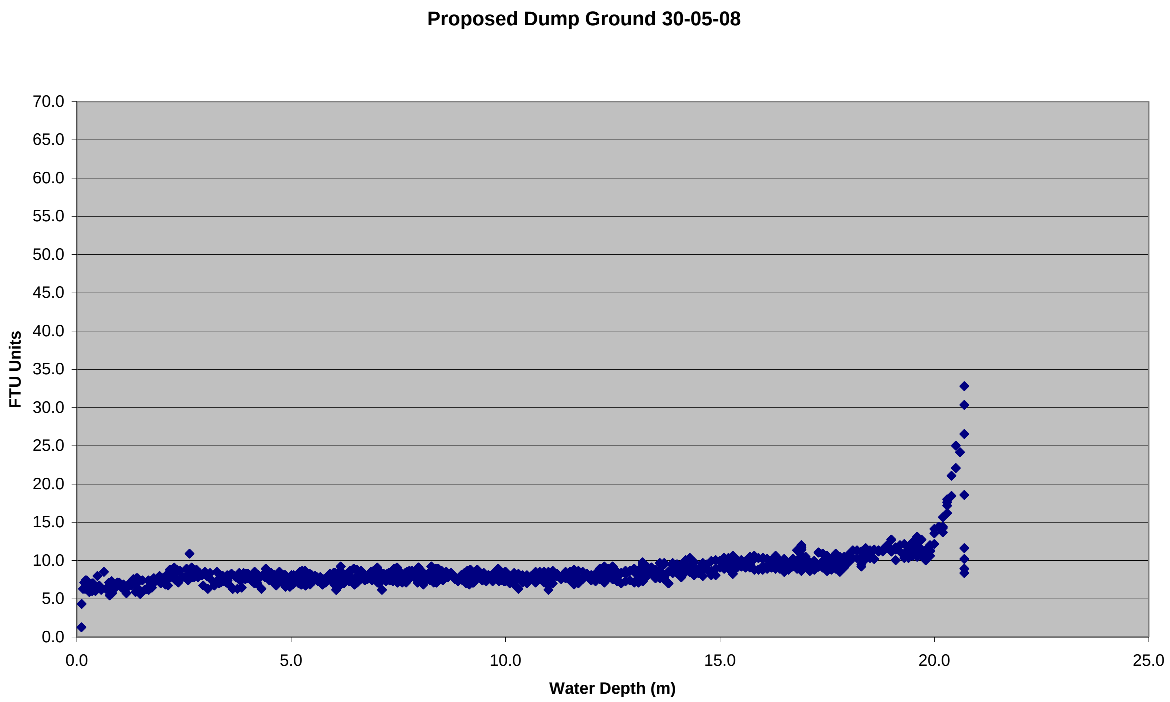


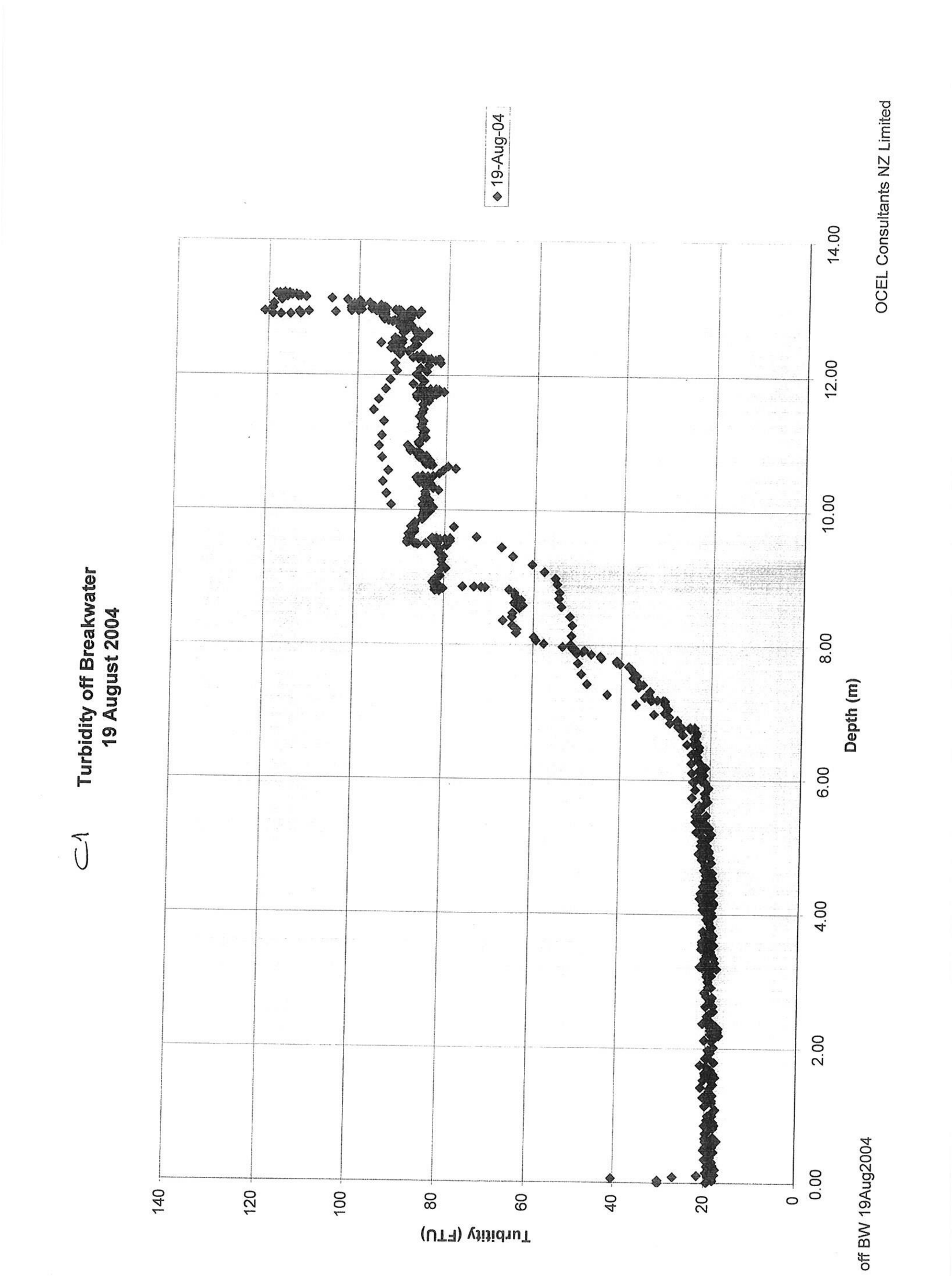
Rapaki Bay 01-07-08
NZMG 5732657 mN, 2488039 mE, 1607 hrs

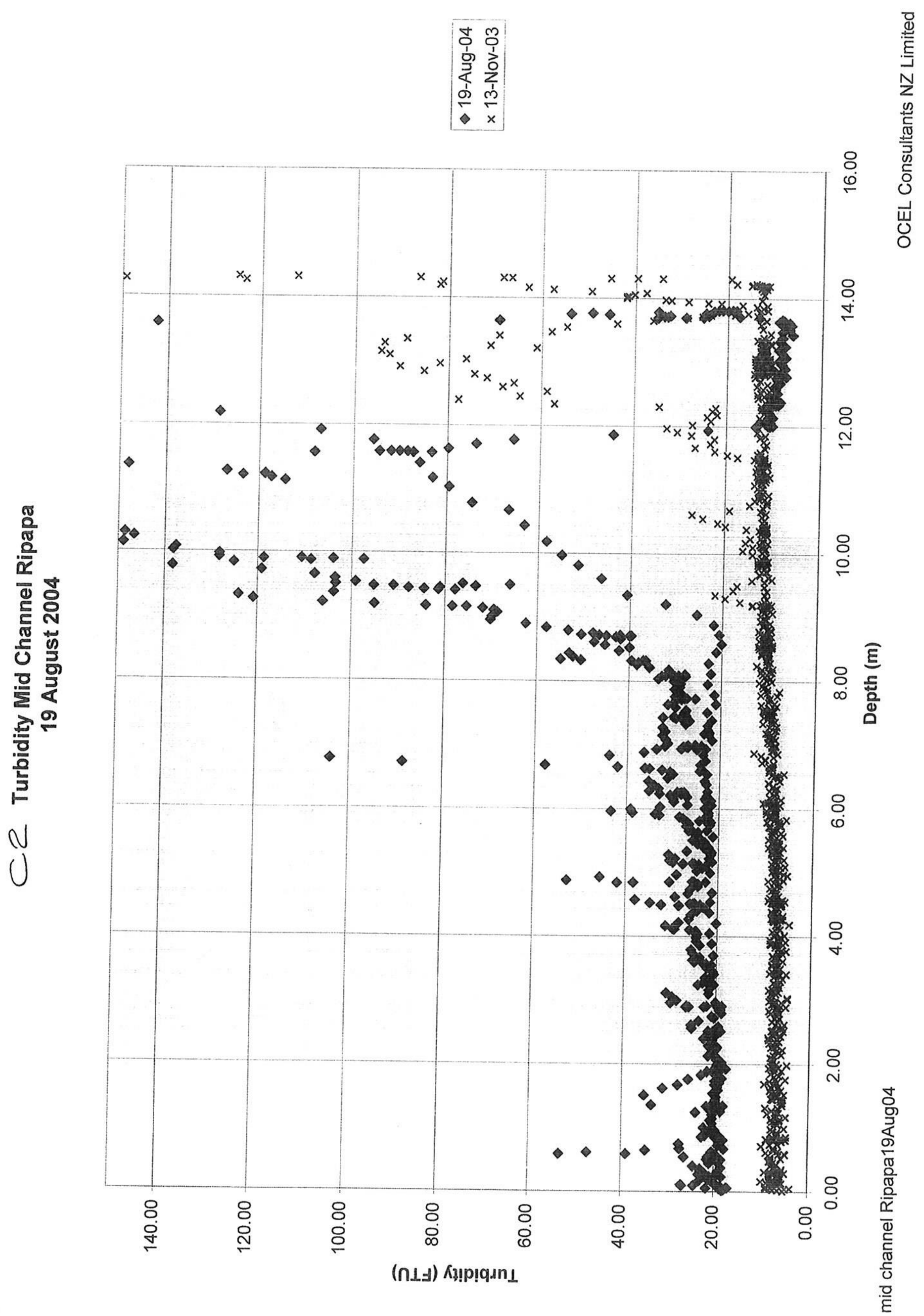


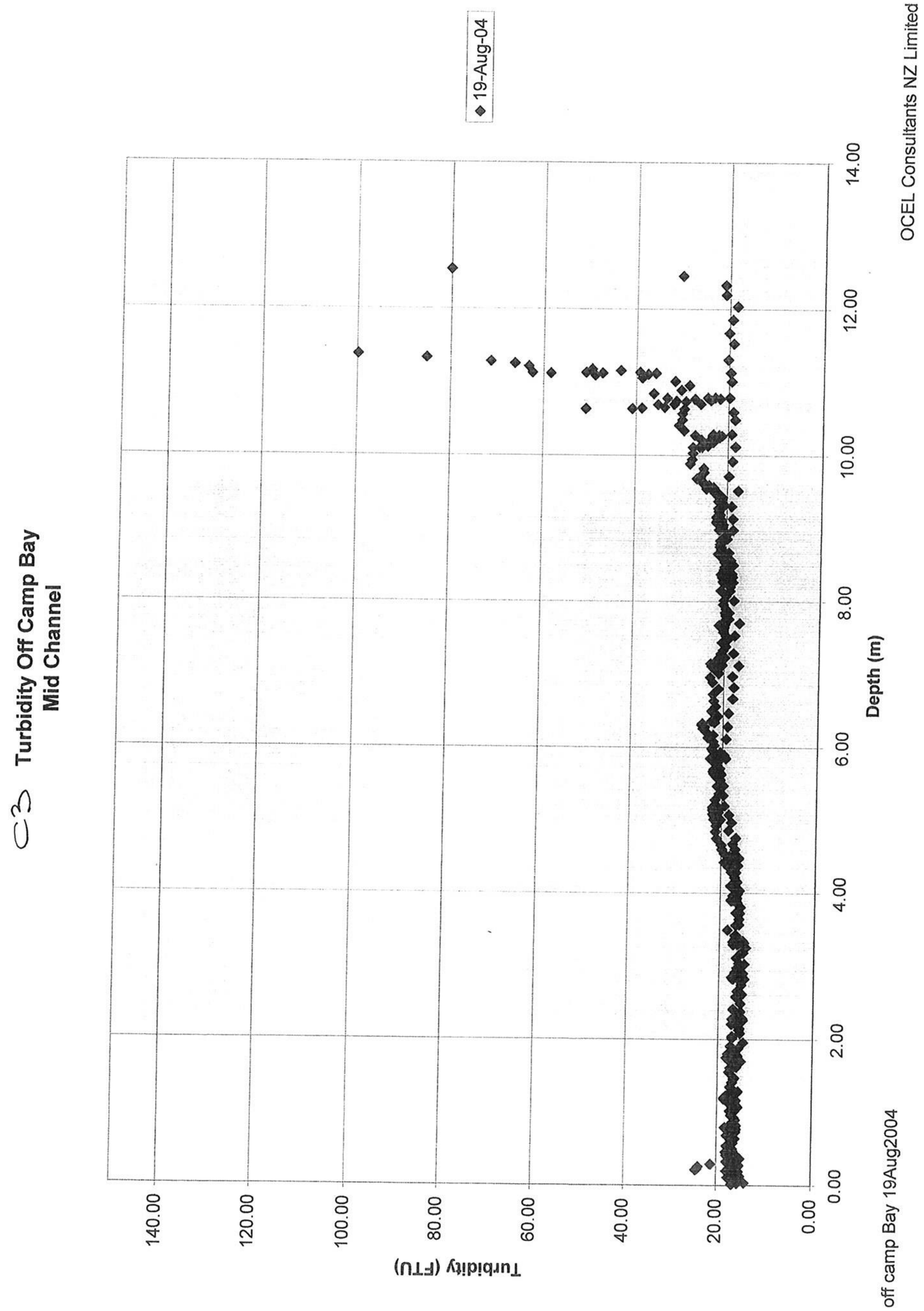

Adderley Head 30-05-08
FTU Units
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Water Depth (m)

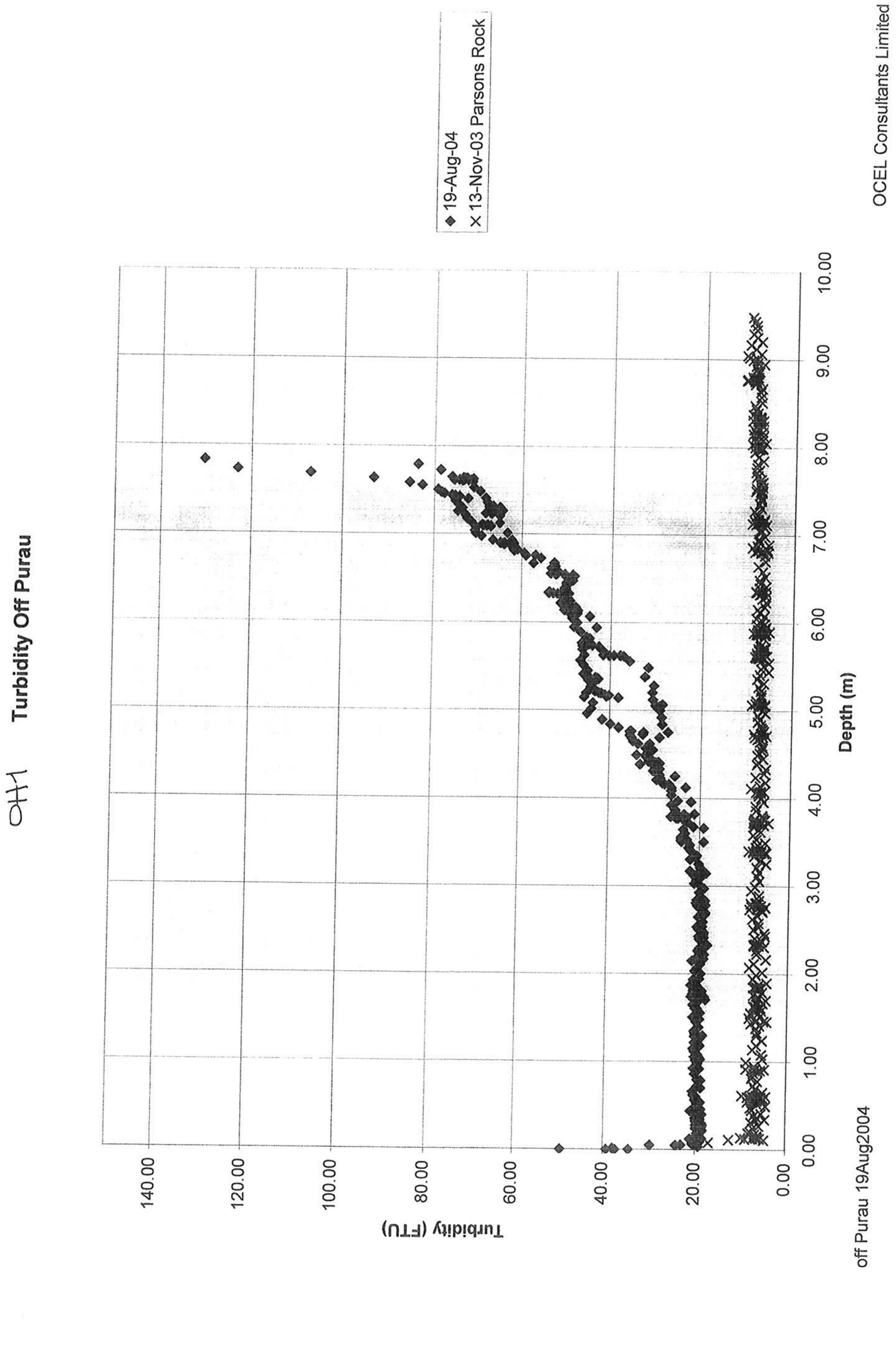

Godley Head 30-05-08
FTU Units
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
Water Depth (m)

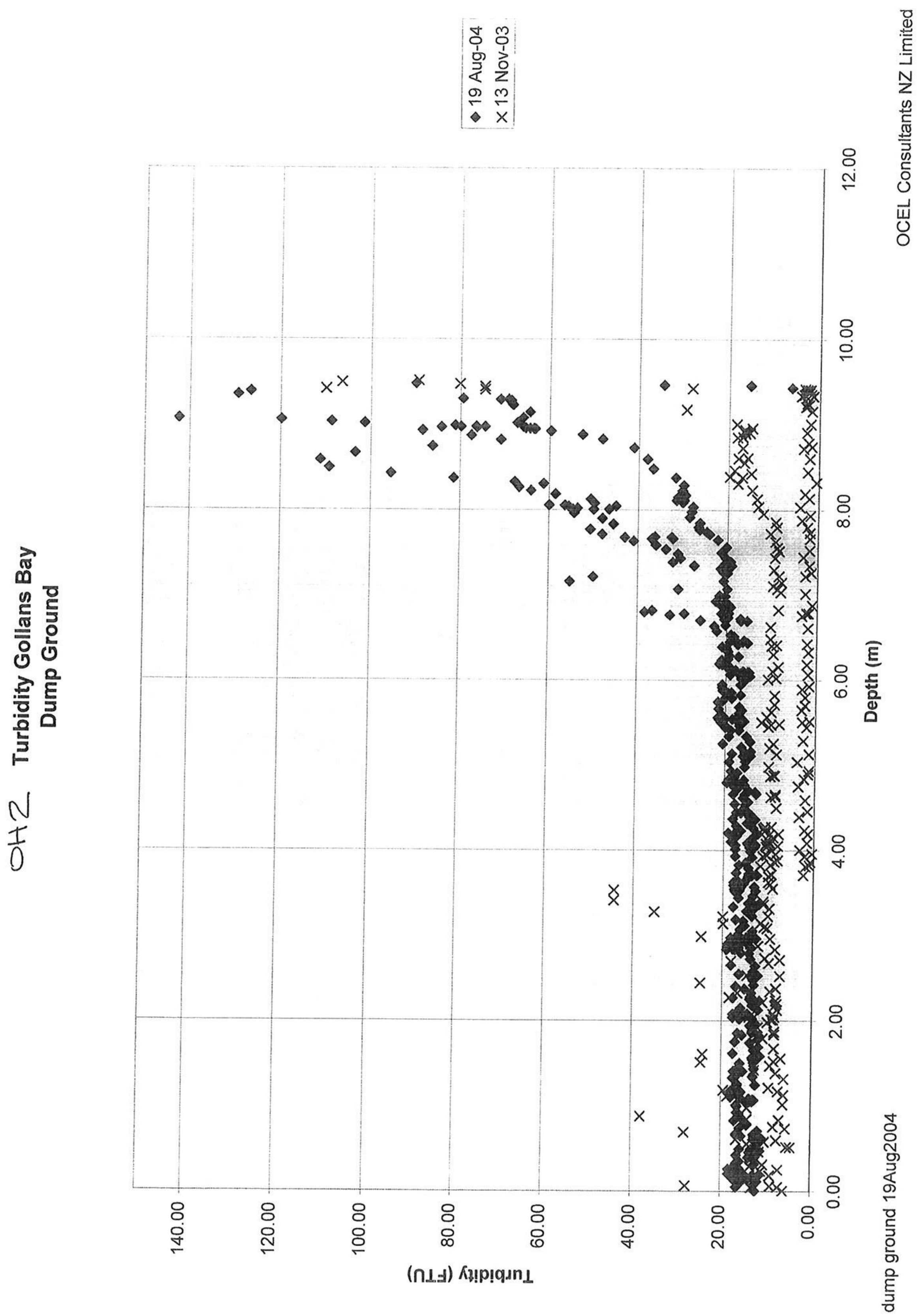

Proposed Dump Ground 30-05-08
FTU Units
70.0
65.0
60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0.0
5.0
10.0
15.0
20.0
25.0
Water Depth (m)

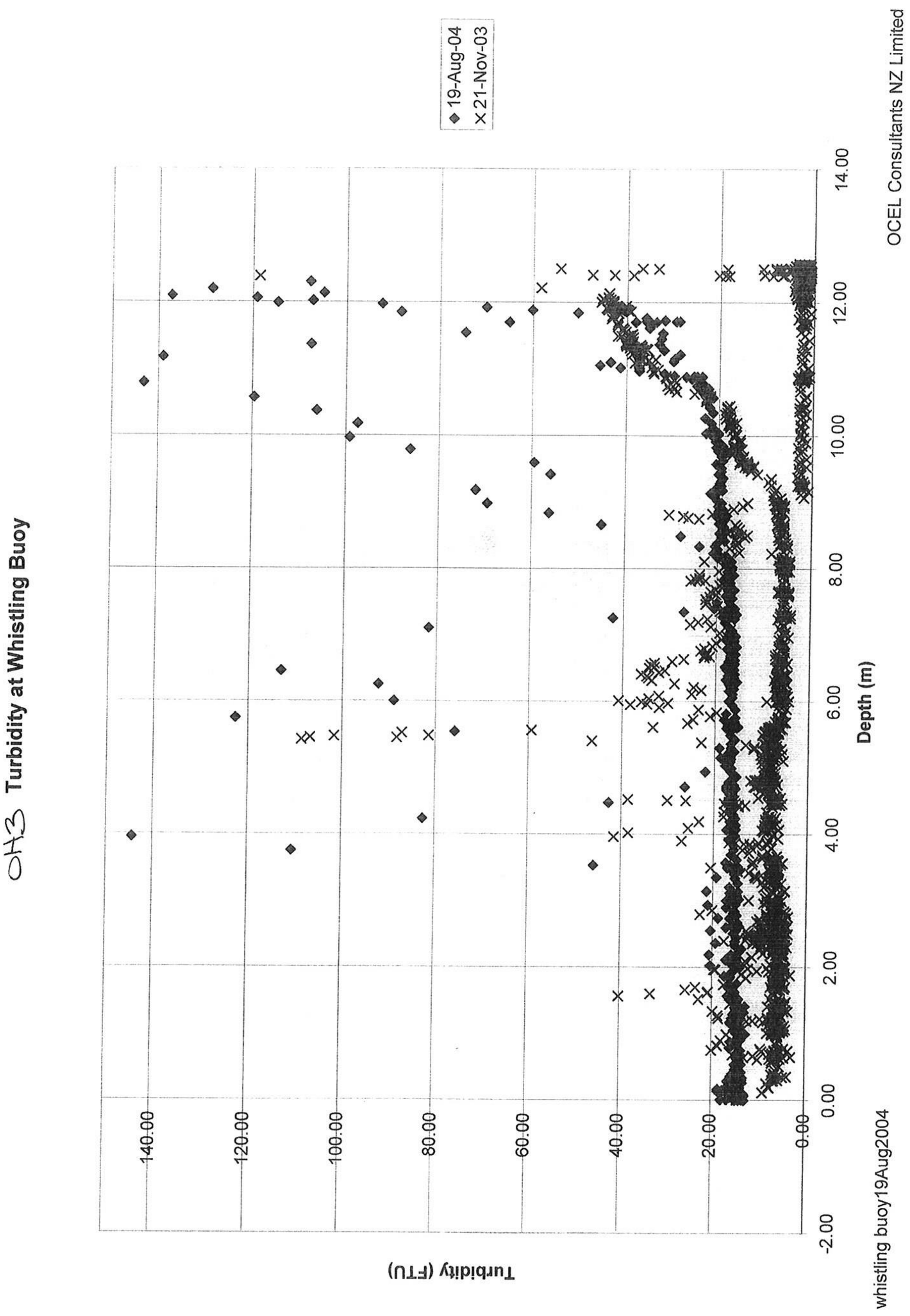

Turbidity off Breakwater
19 August 2004
C1
19-Aug-04
Turbidity (FTU)
0
20
40
60
80
100
120
140
Depth (m)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
off BW 19Aug2004
OCEL Consultants NZ Limited

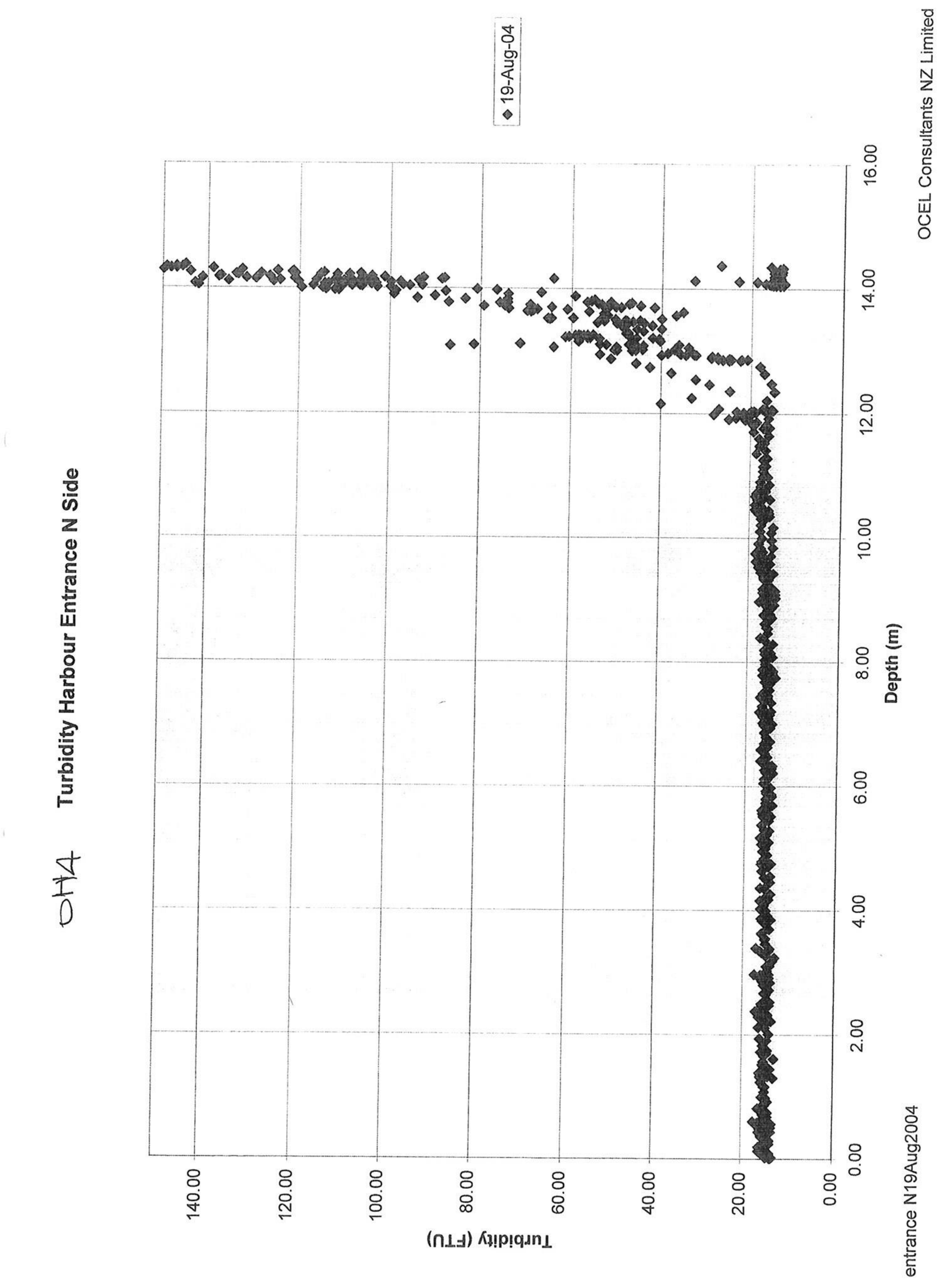

C2 Turbidity Mid Channel Ripapa
19 August 2004
19-Aug-04
13-Nov-03
Turbidity (FTU)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
Depth (m)
mid channel Ripapa19Aug04
OCEL Consultants NZ Limited

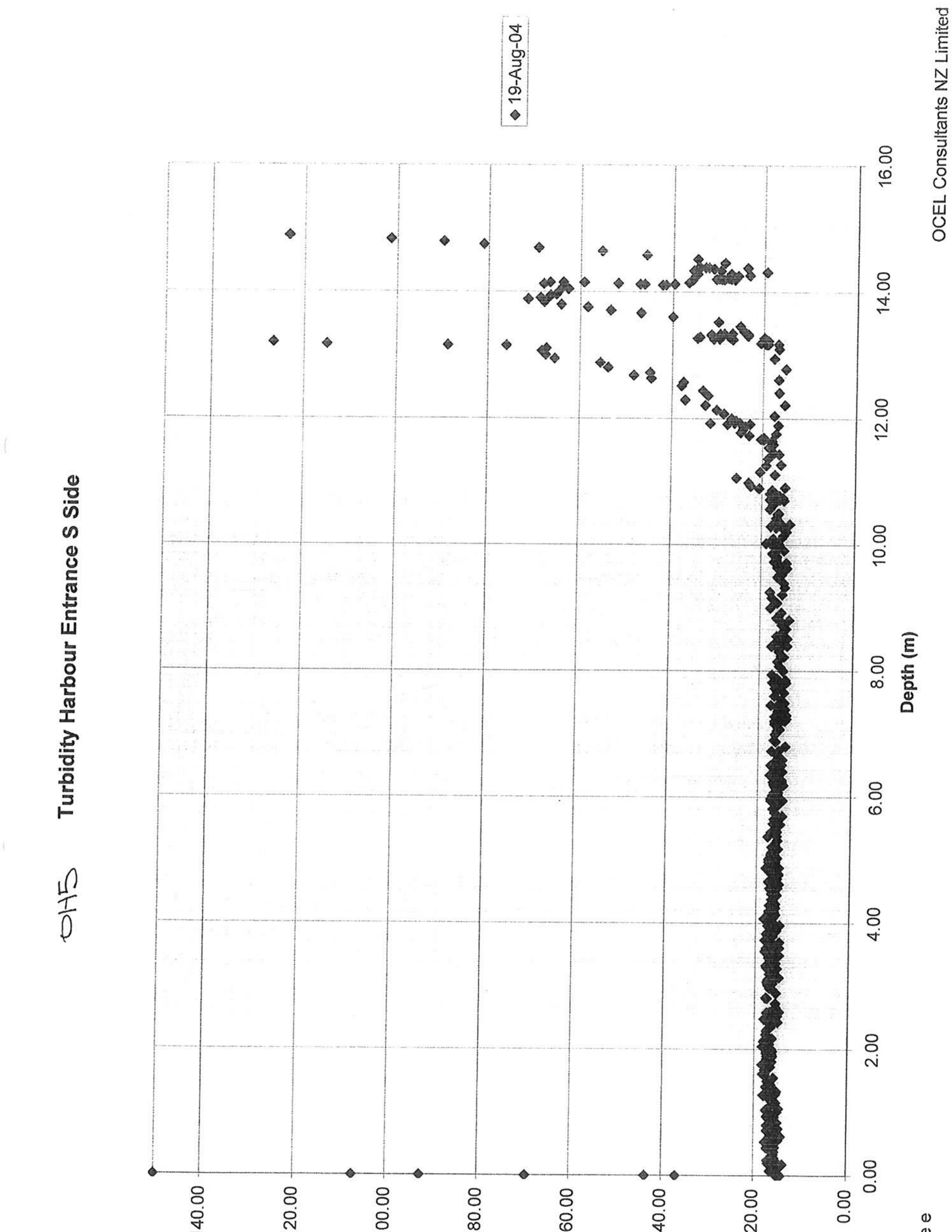

C3
Turbidity Off Camp Bay
Mid Channel
19-Aug-04
Turbidity (FTU)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Depth (m)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
off camp Bay 19Aug2004
OCEL Consultants NZ Limited

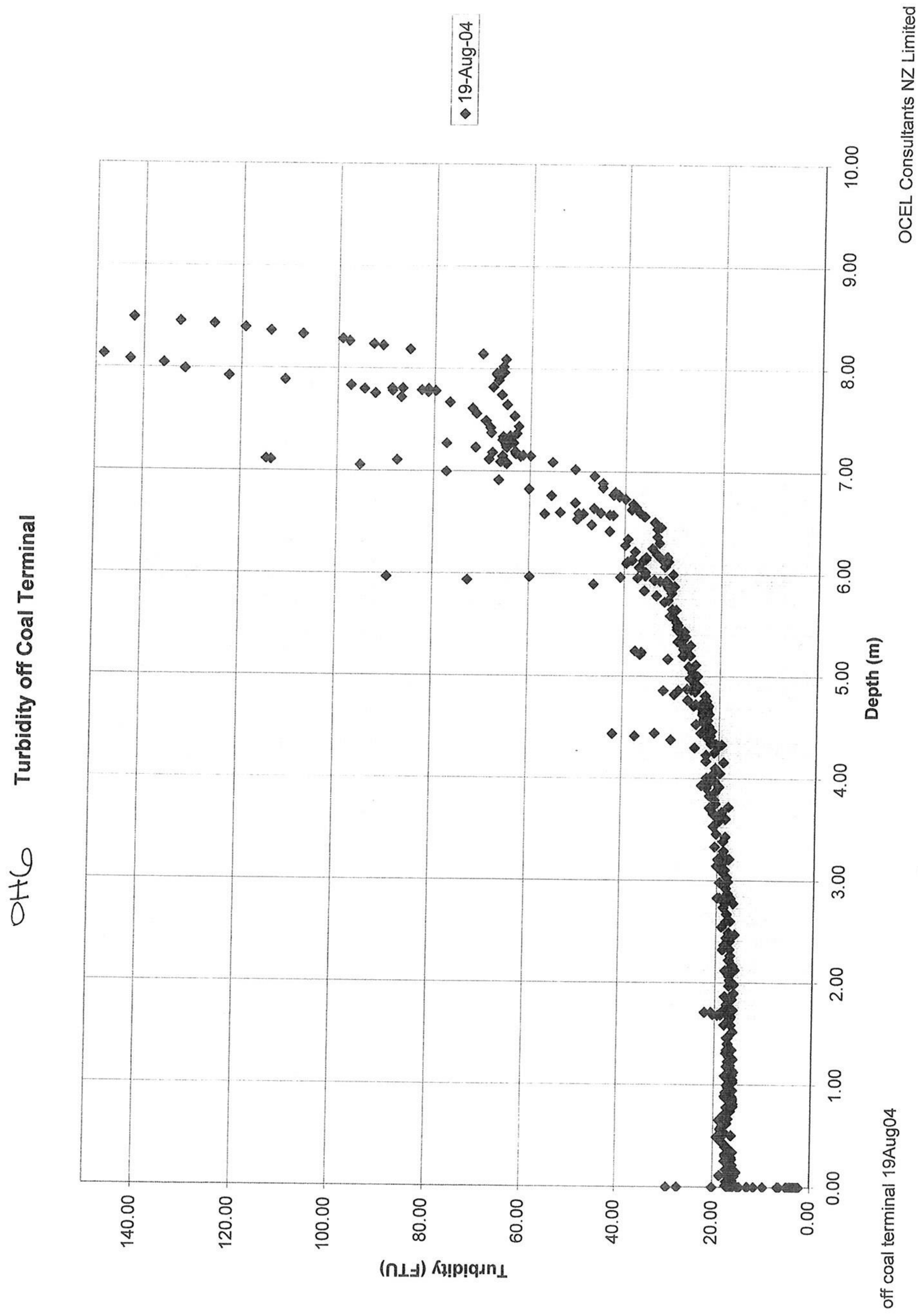

Turbidity Off Purau
19-Aug-04
13-Nov-03 Parsons Rock
Turbidity (FTU)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Depth (m)
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
off Purau 19Aug2004
OCEL Consultants Limited

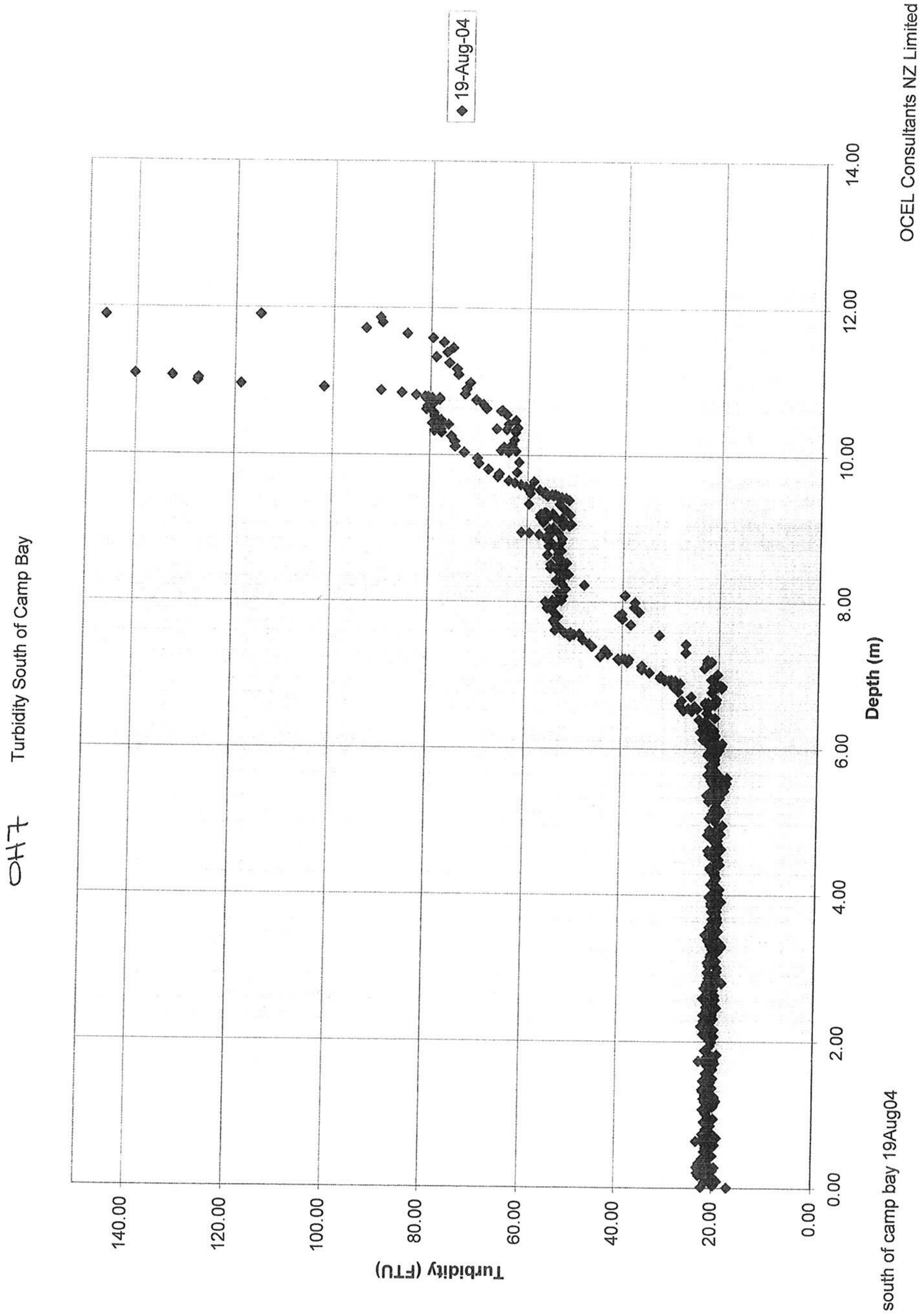

OH2
Turbidity Gollans Bay
Dump Ground
◆ 19 Aug-04
× 13 Nov-03
Turbidity (FTU)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
Depth (m)
dump ground 19Aug2004
OCEL Consultants NZ Limited


OH3 Turbidity at Whistling Buoy
19-Aug-04
21-Nov-03
Turbidity (FTU)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
-2.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
Depth (m)
whistling buoy19Aug2004
OCEL Consultants NZ Limited


OH4
Turbidity Harbour Entrance N Side
◆ 19-Aug-04
Turbidity (FTU)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Depth (m)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
entrance N19Aug2004
OCEL Consultants NZ Limited


Turbidity Harbour Entrance S Side
19-Aug-04
Turbidity (FTU)
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
Depth (m)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
OCEL Consultants NZ Limited
entrance e


Turbidity off Coal Terminal
19-Aug-04
Turbidity (FTU)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Depth (m)
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
OCEL Consultants NZ Limited
off coal terminal 19Aug04


OH7
Turbidity South of Camp Bay
19-Aug-04
Turbidity (FTU)
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
Depth (m)
OCEL Consultants NZ Limited
south of camp bay 19Aug04

APPENDIX D

TSS RESULTS

CRL Energy Ltd

Water Quality Report

OCEL Consultants NZ Limited
276 Antigua Street
Christchurch
Christchurch 8140
Attention: Gary Teear

Report Number: 08/1565
Issue: 1
Date: 21 October 2008

Sample : 08/1565-01
Sample Date : 15/10/2008 **Time**: 00:00
Description : TPAC-00 Trackpack samples
Sample Number 1
Notes : Lyttelton Harbour Channel Extension Project
Order No. :
Date Received : 17/10/2008

Test Code		Result
0120	Turbidity	600 NTU
0121	Suspended Solids	870 g/m3

Sample : 08/1565-02
Sample Date : 15/10/2008 **Time**: 00:00
Description : TPAC-00 Trackpack samples
Sample Number 2
Notes : Lyttelton Harbour Channel Extension Project
Order No. :
Date Received : 17/10/2008

Test Code		Result
0120	Turbidity	60 NTU
0121	Suspended Solids	138 g/m3

Sample : 08/1565-03
Sample Date : 15/10/2008 **Time**: 00:00
Description : TPAC-00 Trackpack samples
Sample Number 3
Notes : Lyttelton Harbour Channel Extension Project
Order No. :
Date Received : 17/10/2008

Test Code		Result
0120	Turbidity	750 NTU
0121	Suspended Solids	935 g/m3

43 Arney Street, Greymouth
Phone (03) 768 0586 Fax (03) 768 0587

Sample : 08/1565-04 **Order No.** :

Sample Date : 15/10/2008 **Time**: 00:00 **Date Received** : 17/10/2008

Description : TPAC-00 Trackpack samples
Sample Number 4

Notes : Lyttelton Harbour Channel Extension Project

Test Code		Result
0120	Turbidity	120 NTU
0121	Suspended Solids	233 g/m3

Sample : 08/1565-05 **Order No.** :

Sample Date : 15/10/2008 **Time**: 00:00 **Date Received** : 17/10/2008

Description : TPAC-00 Trackpack samples
Sample Number 5

Notes : Lyttelton Harbour Channel Extension Project

Test Code		Result
0120	Turbidity	80 NTU
0121	Suspended Solids	191 g/m3

Sample : 08/1565-06 **Order No.** :

Sample Date : 15/10/2008 **Time**: 00:00 **Date Received** : 17/10/2008

Description : TPAC-00 Trackpack samples
Sample Number 6

Notes : Lyttelton Harbour Channel Extension Project

Test Code		Result
0120	Turbidity	160 NTU
0121	Suspended Solids	281 g/m3

All samples analysed as received

Comments:

All testing is performed in accordance with APHA Standard Methods, 21st edition 2005. The methods of analysis and their precision are available on request.

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Malcom Watts
Laboratory Manager

43 Arney Street, Greymouth
Phone (03) 768 0586 Fax (03) 768 0587