ESTIMATING SEDIMENT GENERATION FROM ROCK CONSTRUCTION WORKS

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The dispersal of fine sediments into receiving waters from dredging and disposal associated with major port developments, and the modelling of these, is often a major focus of the environmental approval process for the construction of these works. An aspect that is often overlooked in the environmental assessment of these works is the generation of sediment sourced directly from the construction materials used for breakwater and revetment construction. While fine sediment generation from dredging and offshore sediment disposal is often well documented, there is little guidance or research that has been undertaken in quantifying the direct generation of sediment from the placement of rock armour. This paper demonstrates a method applied to a construction project at Eastland Port NZ to quantify the generation and dispersal of construction-generated fine sediments.

Keywords: water quality, coastal structures, rock armour, hydrometer tests, dry sieve analysis, construction, sediment dispersion modelling,

SEDIMENT SOURCES

There is the potential for fine sediments to be released into receiving waters from construction of coastal protection structures, with fine sediments generated from sediment and dust bound to granular rock fill and underlayer rock when received from local quarries, as well as from minor breakage upon placement.

The release of fine sediments can occur during various phases of the construction process for these structures. A typical construction sequence of activities for a coastal protection and reclamation structure, and the source of fine material associated with each construction activity, is illustrated in Figure 1, and includes:

1. Constructing a working platform from the land side above the high tide level and with a suitable freeboard, to allow access for construction plant. Typically, the platform would be constructed of crushed rock or "quarry run" material, which has the potential to generate a release of fine sediments, from the material bound to the larger individual stones within the quarry run fraction, from weathering during the compaction process, as well as dispersion of the fine fraction included within the quarry run. Often the platform can be incorporated into the core material for the structure.
2. Placement of the structure core (which typically comprises granular "quarry run" material. There is potential for release of fines during this construction phase directly from the fines already present within the core matrix that are released during placement of the material, and due due to erosion of the core caused by wave attack.
3. The working platform is then protected from wave attack by placement of a filter layer, as well as construction of a revetment toe that typically comprises large rock or concrete armour units. Depending on the nature of the seabed, the weight of the armour units can displace soft material and result in generation of sediment. As this fraction is typically sorted to exclude finer fractions, release of fines during this construction phase can occur from the release of the fine material which is bound to the individual armour units prior to placement. Much of the bound material is released immediately upon contact of the armour units with the water column.
4. The revetment is constructed to full height with core and armour, and often extended around the entire reclamation area, prior to filling with reclamation material. This acts as a bund to contain it and prevent release of fines from the reclamation material, which is usually seen as the main source of sediments that can disperse into the environment. The fine material bound to the armour layers on the upper portions of the coastal protection structure is not released immediately but would occur more gradually, due to wetting and drying from wave action and rainfall.

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5. Placement and compaction of reclamation material. This material may typically include dredged sediments from nearby to the project area, which could include sand and silt material, contained within the outer reclamation "bund".
6. During the working life of the structure, there is the potential for further release of fine sediments due to weathering and abrasion of the individual stones, both from minor breakage upon placement and over the lifetime of the structure due to wetting and drying, wave runup and degradation of the rock material. This represents a more minor source of sediment that can impact water quality, but is of interest when considering the design life of a structure due to the gradual reduction in median armour size.

The quantity of fine material bound to core and armour rock used for construction of coastal protection structures is a function of the nature of the rock material received from the quarry, the method of extraction of the rock material from the quarry (blasting and/or excavation), the handling equipment used by the quarry and the procedures in place at the quarry used to process the extracted material (e.g. if the material is washed or screened to remove fines). Core material for coastal protection structures is often specified as "quarry run" which contains fine materials, the placement of which have the potential to result in the release of fine sediments into the environment.

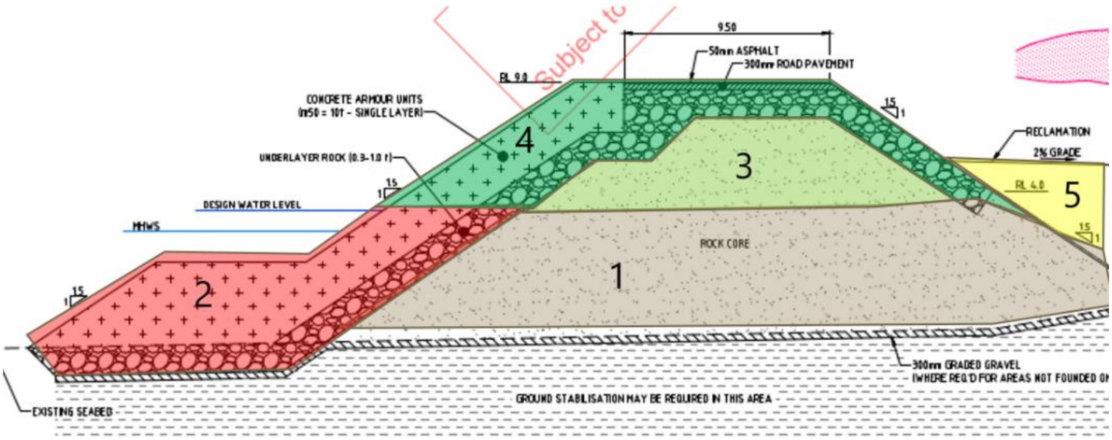

Figure 1. Typical construction sequence for reclamation coastal protection structure. 1. Working platform/placement of core; 2. Construction of toe armour and displacement of seabed sediments; 3. Construction of upper layer of structure core; 4. Placement of upper layers of armour; 5. Placement of reclamation material.

There are no standard tests available to estimate the quantity of fine material that is bound to armour stones produced from a quarry. Theoretical models for estimation of fines content following blasting in a quarry exist (CIRIA, CUR, METCEF 2007). For example, fines generation from minor breakage during handling/transport can be predicted by measuring the average change in the mass of the stones before and after transport. There are also predictive equations that use information such as blast energy and rock fracturing to estimate the percentage of fines, for example the Rosin-Rammler equation (Rosin and Ramler, 1933) provides the basic shape of the particle size distribution of your quarry yield, and the Kuz-Ram model (Cunningham, 1987) for predicting rock fragmentation size distribution by blasting. However, these are quite complex to apply in practice and are not designed to estimate the distribution of the very fine material within the quarry yield that would contribute to poor water quality. The models also do not predict contamination of the quarry material with fines from sources other than derived from the blasting process.

Jiang et al (2019) describes best practice for sediment plume dispersion model application, including *spill* rates (release of fine materials into the water column as a percentage of the mass or volume of material placed) to use for sediment plume modelling for different construction activities. However, these are sourced from field studies of sediment placement for reclamation and are not specifically for generation of sediment from rock used for breakwater construction. For construction of the core of a coastal protection structure, one potential approach is to use results from measured spill rates for dumping of dredge material with an unknown quantity of fines and onto a silt/clay seabed. For that scenario, the recommended "spill" rate is 6%, which would be a conservative estimate for the core construction and considers resuspension of fine material from the seabed during construction.

METHOD AND RESULTS

To obtain a more realistic estimate of the fine sediment "spill" rate from construction of core and armour layers due to fine sediments bound to the rock, two samples of "quarry run" material were tested using both dry sieve analysis (DSA) and hydrometer testing, one representing "all in" quarry run and the other "plus 65", with fines screened.

Figure 2. Quarry run sample used in hydrometer analysis

The results of the DSA test for the "all-in" material provided an initial estimate for the silt fraction of 4.9%, as indicated in Table 1. While this result was comparable with the 6% "spill" rate for dumping of dredge material with an unknown quantity of fines and onto a silt/clay seabed, the result from the DSA was not considered suitable for dispersion modelling, or representative of the fine material that would be released during construction, for the following reasons:

- For plume modelling, the assumption is often made that the sediment particles are spherical, and that Stokes' Law (Stokes, 1851) can be used to estimate the fall velocity for each particle of different size. However, the particles are not necessarily spherical, and fall velocity is not always well described by Stokes' Law, so it is preferable to measure the fall velocity directly rather than rely on particle size distribution alone to estimate the fall velocity.
- The DSA provides particle size distributions to 75 mm. For sediment plume dispersion modelling, fall velocities for different classes of materials smaller than 75 mm are required, together with an estimate of the distribution of this material fraction.
- Further, it was postulated that the DSSA would not be representative of all the materials released into the water column during construction, as it may not include all of the fraction of fine material bound to the armour units.

Table 1 – Summary of Dry Sieve Analysis for "all-in" quarry run material						
Size (mm)	% Passing	Weight (Kg)	Passing Kg/ Tonne	Retained (Kg/Tonne)	% per tonne passing	% per tonne retained
300	100.0%	119.85	1,000.00	202.00	100.0%	20%
200	79.8%	95.64	798.00	145.00	79.8%	15%
100	65.3%	78.26	653.00	122.00	65.3%	12%
63	53.1%	63.64	531.00	223.00	53.1%	22%
37.5	30.8%	36.91	308.00	72.00	30.8%	7%
19	23.6%	28.28	236.00	48.00	23.6%	5%
9.5	18.8%	22.53	188.00	42.00	18.8%	4%
4.75	14.6%	17.50	146.00	18.00	14.6%	15%
2.36	12.8%	15.34	128.00	24.00	12.8%	
1.18	10.4%	12.46	104.00	19.00	10.4%	
0.6	8.5%	10.19	85.00	13.00	8.5%	
0.3	7.2%	8.63	72.00	11.00	7.2%	
0.15	6.1%	7.31	61.00	12.00	6.1%	
0.075	4.9%	5.87	49.00		4.9%	

The hydrometer test was undertaken on a 1 kg subsample of the "quarry run" fraction below 4.75 mm diameter, providing the particle size distribution of the finer fraction of the material "in the wet", with particle size distribution down to fine silt or finer (0.0012 mm). The hydrometer test is representative of the generation of fines from end-dumping of the core material within the water column as it includes the fraction that would be released from the core on contact with the water (i.e. the fines do not remain bound to the larger fraction as would occur in a dry sieve analysis).

The hydrometer test also provided the fall velocities for these fine fractions, which are important inputs used in sediment dispersion modelling. It was found that for the "all-in" material, 7.01% of the mass of the material entering the water column would be silt-sized particles or finer that could contribute to a plume (Table 2), reducing to 1.2% for the pre-screened material (Table 3).

Table 2 – Summary of hydrometer analysis for "all-in" quarry run material							
Size (mm)	% Passing	Weight (Kg)	Passing Kg/ Tonne	Retained (Kg/Tonne)	% per tonne passing	% per tonne retained	Fall velocity cm/sec
4.75	100.0%	17.50	146.00		14.60%	1.02%	
2.36	93.0%	16.27	135.78		13.58%	1.90%	
1.18	80.0%	14.00	116.80		11.68%	1.61%	
0.6	69.0%	12.07	100.74		10.07%	0.58%	
0.425	65.0%	11.37	94.90		9.49%	0.44%	
0.3	62.0%	10.85	90.52		9.05%	0.44%	
0.212	59.0%	10.32	86.14		8.61%	0.44%	
0.15	56.0%	9.80	81.76		8.18%	1.17%	
0.075	48.0%	8.40	70.08	2.92	7.01%	0.29%	
0.063	46.0%	8.05	67.16	7.30	6.72%	0.73%	
0.0353	41.0%	7.17	59.86	4.38	5.99%	0.44%	0.11900
0.026	38.0%	6.65	55.48	2.92	5.55%	0.29%	0.06438
0.0188	36.0%	6.30	52.56	4.38	5.26%	0.44%	0.03382
0.0138	33.0%	5.77	48.18	2.92	4.82%	0.29%	0.01813
0.0103	31.0%	5.42	45.26	2.92	4.53%	0.29%	0.01010
0.0075	29.0%	5.07	42.34	5.84	4.23%	0.58%	0.00538
0.0055	25.0%	4.37	36.50	2.92	3.65%	0.29%	0.00291
0.004	23.0%	4.02	33.58	2.92	3.36%	0.29%	0.00151
0.0029	21.0%	3.67	30.66	4.38	3.07%	0.44%	0.00078
0.0022	18.0%	3.15	26.28	4.38	2.63%	0.44%	0.00047
0.0012	15.0%	2.62	21.90	21.90	2.19%	2.19%	0.00015

Table 3 – Summary of hydrometer analysis for "plus-65" quarry run material							
Size (mm)	**% Passing**	**Weight (Kg)**	**Passing Kg/ Tonne**	**Retained (Kg/Tonne)**	**% per tonne Passing**	**% per tonne retained**	**Fall velocity cm/sec**
4.75	100.0%	2.44	24.00		2.40%	0.14%	
2.36	94.0%	2.29	22.56		2.26%	0.19%	
1.18	86.0%	2.09	20.64		2.06%	0.22%	
0.6	77.0%	1.88	18.48		1.85%	0.10%	
0.425	73.0%	1.78	17.52		1.75%	0.10%	
0.3	69.0%	1.68	16.56		1.66%	0.10%	
0.212	65.0%	1.58	15.60		1.56%	0.10%	
0.15	61.0%	1.49	14.64		1.46%	0.26%	
0.075	50.0%	1.22	12.00	0.72	1.20%	0.07%	
0.063	47.0%	1.14	11.28	0.72	1.13%	0.07%	
0.0353	44.0%	1.07	10.56	0.96	1.06%	0.10%	0.12253
0.026	40.0%	0.97	9.60	0.72	0.96%	0.07%	0.06763
0.0188	37.0%	0.90	8.88	0.96	0.89%	0.10%	0.03626
0.0138	33.0%	0.80	7.92	0.24	0.79%	0.02%	0.01976
0.0103	32.0%	0.78	7.68	0.96	0.77%	0.10%	0.01075
0.0075	28.0%	0.68	6.72	0.72	0.67%	0.07%	0.00581
0.0055	25.0%	0.61	6.00	0.72	0.60%	0.07%	0.00307
0.004	22.0%	0.54	5.28	0.48	0.53%	0.05%	0.00159
0.0029	20.0%	0.49	4.80	0.48	0.48%	0.05%	0.00082
0.0022	18.0%	0.44	4.32	0.72	0.43%	0.07%	0.00049
0.0012	15.0%	0.37	3.60	3.60	0.36%	0.36%	0.00015

The silt-sized fractions would settle at different rates, with settling velocities provided in Table 2 and Table 3, with the assessed settling velocities being important inputs for dispersion modelling of the fines generation from revetment construction. It is postulated that during construction, fines would only enter the water from the fraction of the core in contact with the water, or from approximately 75% of each load of end-tipped material during the construction.

An additional aspect to be considered is the flocculation of fine sediments in sea water, whereby fine colloidal particles are negatively charged on their surface and tend to repel each other (Mosley et al. 2020). In high salinity environments such as in sea water, positive ions from the salt water interact with the negatively charged clay particles which then attract each other and flocculation occurs, resulting in the clay particles aggregating together and increasing the fall velocity. Ideally, the hydrometer test should be conducted using water with the same salinity as the receiving waters as the construction project, but if this is not possible then the flocculation process needs to be considered within the sediment transport modelling.

The hydrometer analysis and the proposed armour placement program allowed the development of an estimate of the fine sediments to use as input in a coupled wave-current sediment transport model and model the fate of the plume generated during the construction works.

The differential between the hydrometer analysis and DSA is illustrated in Figure 3. The hydrometer analysis provides a higher fraction of silt material than the DSA, with 7.2% of the material by mass being silt sized or smaller in the hydrometer analysis, but only 4.9% being silt sized or smaller from the DSA. An estimate of the portion of fine particles that are bound to the armour rock can be deduced from the portion of fines that are not captured by the dry sieve analysis (2.3%).

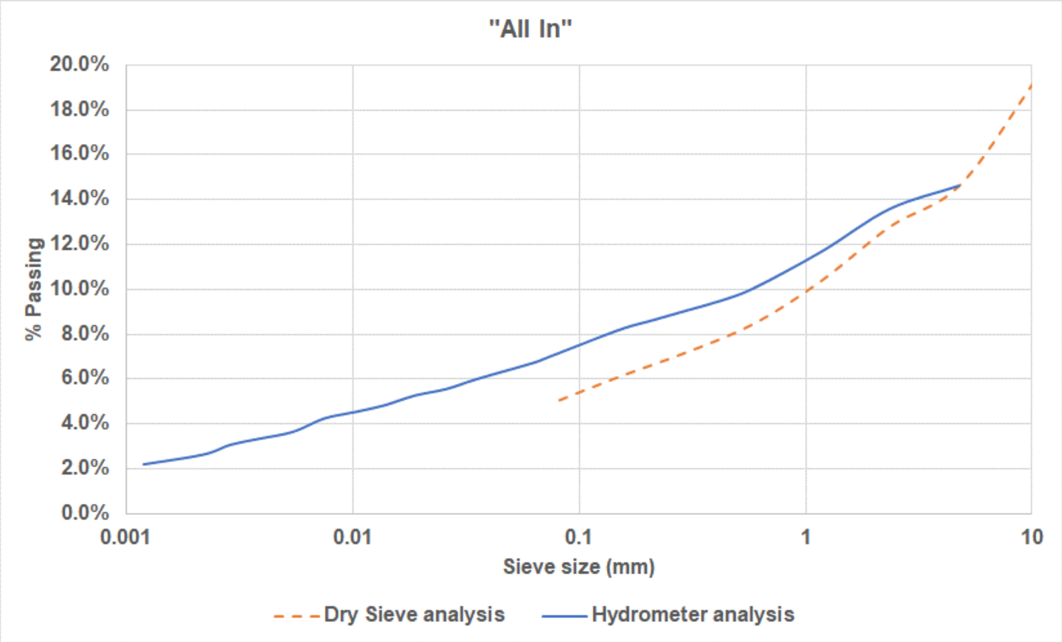

Figure 3. Differential between hydrometer results (solid line) and Dry Sieve Analysis (dashed line) for "all-in" quarry run material showing the portion of fines not captured by the Dry Sieve Analysis.

For the washed "Plus 65" sample, there was close agreement between the dry sieve analysis and wet sieve analysis, as illustrated in Figure 4. It is postulated that the pre-washing of the sample released the fine particles that were bound to the rock. In addition, it was noted that 1.2% of the washed sample contained silt-sized fines, compared with 7% for the "all in" sample, which illustrates the effectiveness of pre-washing the material as a mitigation measure to reduce the load of fines entering the receiving waters during construction.

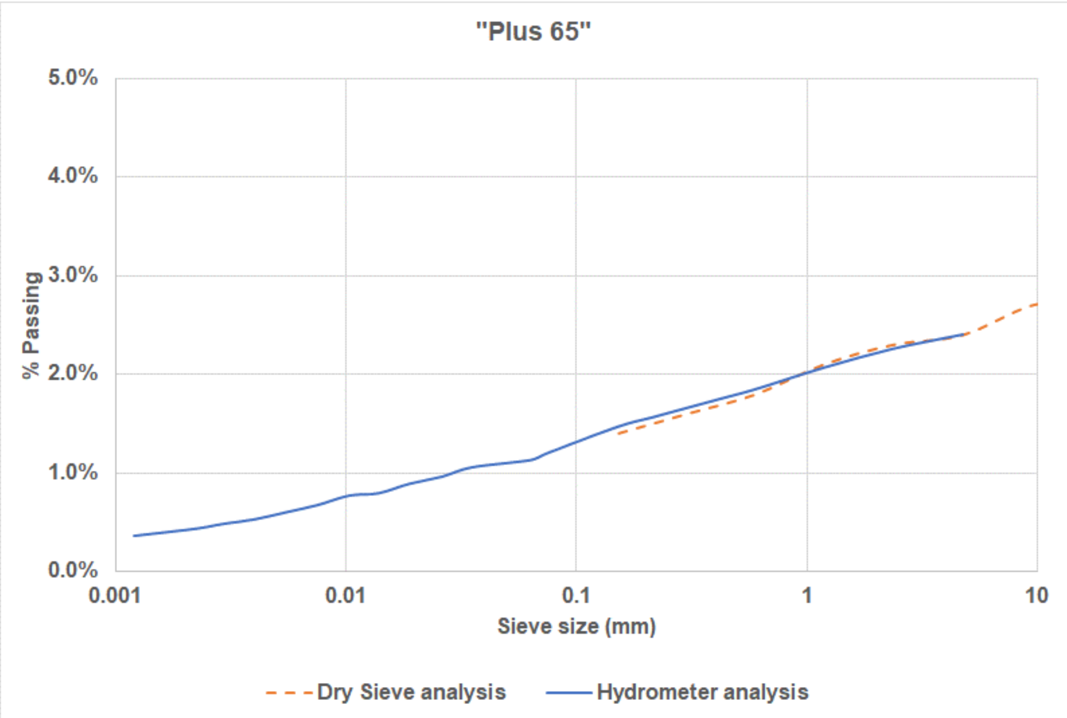

Figure 4. Differential between hydrometer results (solid line) and Dry Sieve Analysis (dashed line) for "plus-65" quarry run material.

A calibrated and validated Delft3D model was used to simulate the dispersion of sediments that could potentially be released during the reclamation works. The main model domain (

Figure 6) includes the entire Poverty Bay with a grid resolution ranging from approximately 6 m to 250 m, with higher resolution in the port area. This grid is nested to a coarser grid used in the wave module. The model ran in 3D mode to replicate both the baroclinic and the barotropic dynamics within Poverty Bay.

The simulations were carried out for fifteen days (07/07/2002 to 23/07/2002) characterised by some peaks of high energy wave conditions (max Hs approx. 1.4 m, Figure 5) and large river flows (max. discharge rate Waipaoa = 7.99 m^3/s; max. discharge rate Turanganui = 30.09 m^3/s). No sediment was discharged from the rivers, the only source of sediment is from the reclamation work.

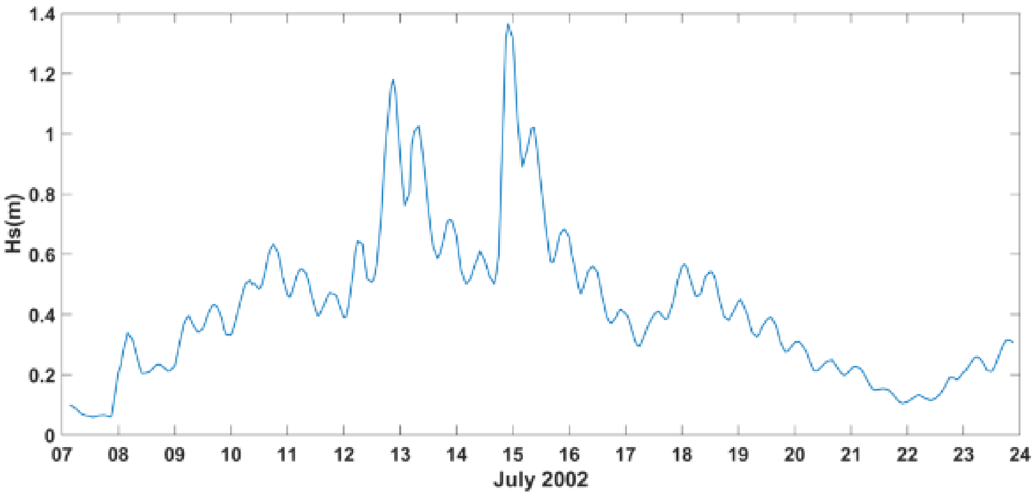

Figure 5. Time series of significant wave height (Hs) at the reclamation area (2036982, 5770114).

The modelled scenario represents the protection bund partially built, and a fixed source of sediment discharge representing release of fine sediments from the surface of the rocks (

Figure 6, right). Release of sediment was for the full duration of the simulation (15 days), during working hours (7 am to 5 pm).

The "plus 65" material was chosen as more representative of the proposed work plan and in an effort to mitigate potential release of fines. Three sediment size classes (35 µm, 10 µm, and 2 µm) were chosen for the modelling, representing 0.41%, 0.26%, and 0.53% of the fine material, respectively. For each of the 3 sediment classes, two different settling velocities were used, without flocculation using results from the hydrometer analysis, and with flocculation of fine particles that occur in seawater. To account for resuspension of sediment that might eventually settle within the model domain, a low critical shear stress (0.18 $N.m^{-2}$) was applied over the domain based on a weakly-consolidated material (Van Rijn, 2016).

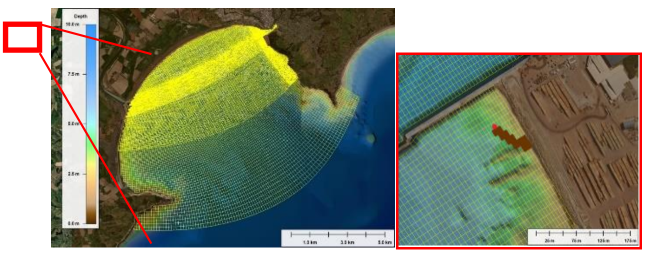

Figure 6. Delft3D domain (left) and details of the grid at the reclamation area (right). Dry cells (in brown) represent a partial reclamation wall and the location of the source of sediment is shown by the red circle.

Model results show sediment plume concentration near the port is likely to be <=0.02 kg.m-3 above background concentration, which is typically 0.13 to 0.23 kg/m3 (4Sight 2019). The plume represents a minor increase comparatively, corresponding to 5x to 10x less the background concentration range within the port area. Further into Poverty Bay, outside the port area, background concentration is typically 0.02 kg/m^3 and the model results show plume of less than 0.002 kg/m^3, above background, indicating that plume might have a minor contribution to the background suspended sediment concentration.

Deposition of the fine sediments on the seabed occurs mostly west of the reclamation site, along the southern side of the breakwater, and at the entrance of the port and navigation channel. These areas show most of the deposition is <0.001 m (1 mm). A narrow depositional area along the southern side of the breakwater shows higher deposition with a maximum of approximately 0.002-0.003 m.

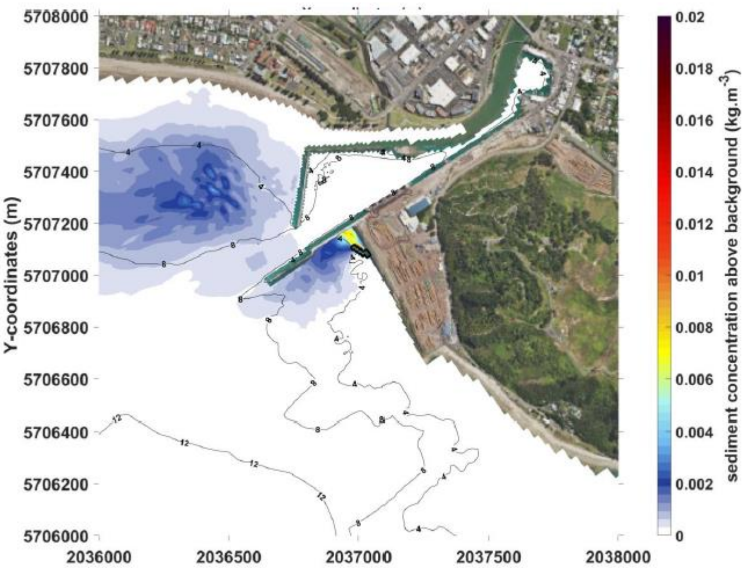

Figure 7. 50th percentile maps of sediment concentration (kg/m3) at bottom for scenario without flocculation ("plus 65 hydro").

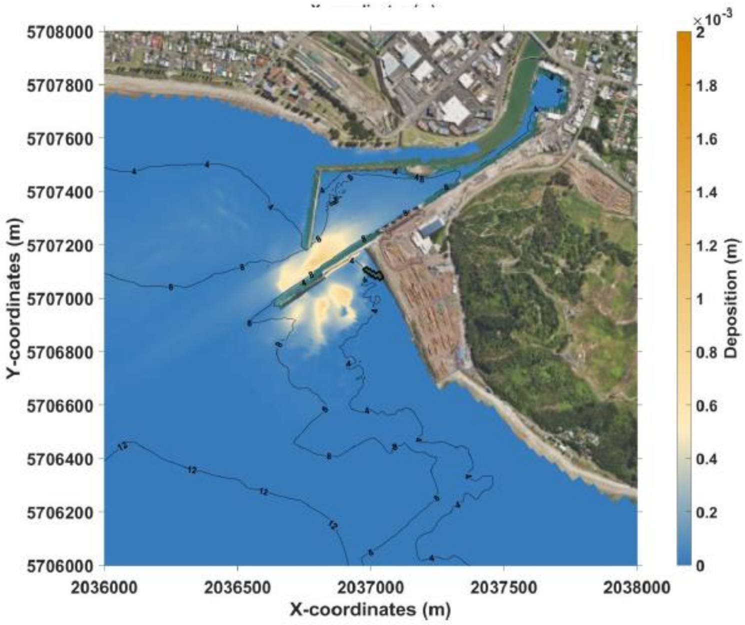

Figure 8. Sediment deposition (m) at the end of 15-day simulation for scenario without flocculation ("plus 65 hydro").

CONCLUSIONS

Hydrometer testing is a simple laboratory-based analysis that can be used to assess the "spill rate" for generation of sediment from quarry materials used for construction. It also provides the sediment settling velocities for the finer fractions of this material, which are required for sediment dispersion modelling, and accounts for the generation of the fine fraction of material bound to the larger fractions that cannot be derived using standard dry sieving methods.

To estimate the effect of flocculation of fine sediments, the salinity of the receiving waters should be considered and the test be conducted using water of the same salinity as the receiving waters.

The results of the hydrometer analysis and sediment transport modelling indicated that pre-washing core and armour material to be used in the construction of coastal structures can be an effective mitigation measure to reduce the load of fines entering the receiving waters during construction.

The hydrometer analysis indicated a reduction in fines content from 7% to 1.2% between the "all-in" sample and the "plue-65" sample.

The sediment transport modelling results showed that the concentration of fine sediments within the plume from construction using the Plus 65 material would be less than 0.02 kg/m^3 above background levels, which is between 10 and 20% of the typical background concentration for the area around Eastland Port.

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