Modeling Drill Cuttings Sedimentation on Corals for Exploration Wells Z-1 and B-1, Offshore Sabah

Su Yean Teh and Hock Lye Koh

***Abstract*—Oil well drilling activities generate residues called drill cuttings that will be treated before being disposed onsite. When drill cuttings are released into the sea, drill cutting piles or mounds will form on the seabed. These pile formations may hinder future under-sea operation. They may have adverse impacts on corals if the thickness of the pile over the coral beds is persistently high. This simulation study is conducted at the drill cuttings release sites Z-1 and B-1 in the South China Sea off the coast of Sabah. This modelling study will assess the potential impacts of the pile formation on coral community and on the ecology in the dive site (shipwreck) nearby. For Z-1, the particles settle on the seabed far away from the corals and far away from the shipwreck sites. Hence they will have no adverse impact on the corals nor on the shipwreck site environment and ecology. For B-1, the coral site is located at a shorter distance from the discharge location. The pile height at the coral site varies between 0.05 mm to 0.5 mm. The average sedimentation rate varying between 3.1 to 31 mg/cm^2/day occurs over a short duration of 3.875 days. This low sedimentation rate over a short duration will have insignificant impact on the corals.**

***Index Terms*—Corals, drill cuttings, oil and gas, TUNA-PT.**

I. Introduction

A simulation study is commissioned to assess the potential environmental impacts of drill cuttings sedimentation on the coral communities and on other environmentally sensitive sites including a shipwreck in the vicinity of the two proposed exploration wells located at B-1 (5°49'N, 115°8'E) and Z-1 (5°17'N, 114°59'E). When drill cuttings are released into the sea, drill cutting piles or mounds will form on the seabed. A major objective of this study is to ensure that the sedimentation or pile formation on the seabed will not have adverse impacts on the coral communities nor on the ecosystem in the shipwreck dive site nearby. This study will perform model simulations on particle deposition onto the seabed to determine the location and sediment thickness distributions, with particular reference to sedimentation over coral beds. Based upon the simulation results, sediment thickness (mm) and sedimentation rate (mg/cm^2/day) due to the settling of drill cuttings on the coral will be estimated in order to assess the potential impacts of sedimentation on coral community and on the environment of dive site nearby.

Fig. 1 shows the locations of the two study sites (Z-1 and B-1) relative to Pulau Tiga, a marine park nearby. Further, K1 is Kimanis-1 located within the Kimanis Bay, K2 is Kimanis-2 located at the mouth of Kimanis Bay and KBB is the Kebabangan Oil & Gas Platform. Met-ocean data available at Kimanis and Kebabangan platforms [1] will be used in this study. Fig. 2 indicates the distances from the drill cutting release site or well at Z-1 to the coral site and shipwreck site nearby, which are 500 m and 1000 m respectively. Corresponding figures for B-1 are omitted due to space constraint.

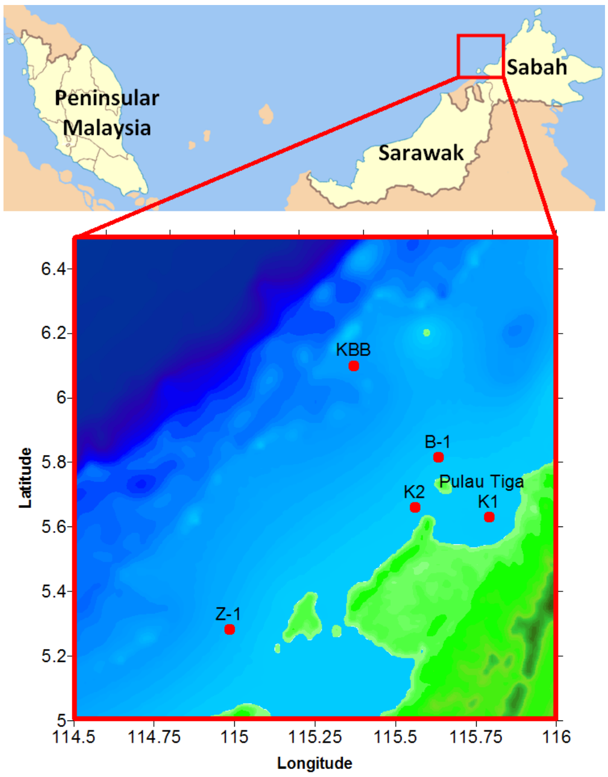

Fig. 1. Map indicating study sites B-1 and Z-1. K1 is Kimanis-1 located within the Kimanis Bay, K2 is Kimanis-2 located at the mouth of Kimanis Bay, and KBB is Kebabangan Oil & Gas Platform.

Fig. 3 (left) depicts predominant surface currents in the South China Sea during January (Northeast Monsoon). Currents enter the South China Sea at the northern entrance and exit at the southern entrance. The predominant currents along the Sabah coast flow towards the northeast. Fig. 3 (right) demonstrates predominant surface currents in the South China Sea during July (Southwest Monsoon). Currents enter the South China Sea at the southern entrance and exit at the northern entrance. The predominant currents along the Sabah coast flow also towards the northeast. Details regarding current in the South China Sea are available elsewhere [2], [3]. The currents and eddies facilitate the efficient removal of sediments settling on the corals.

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S. Y. Teh is with the School of Mathematical Sciences, Universiti Sains Malaysia, 11800 USM, Pulau Pinang, Malaysia (e-mail: syteh@usm.my).

H. L. Koh is with the Sunway University Business School, Jalan Universiti, Bandar Sunway, 47500 Selangor Malaysia (e-mail: hocklyek@sunway.edu.my).

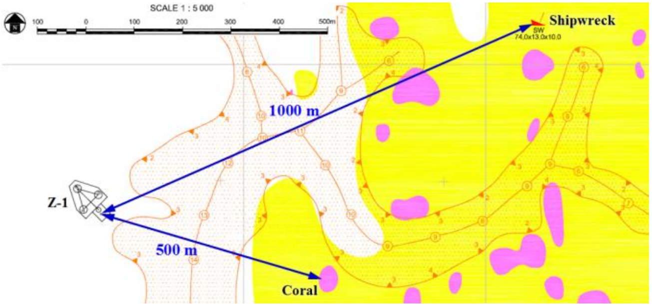

Fig. 2. Distances from drill cutting release site at Z-1 to coral site (500 m) and shipwreck site (1000 m).

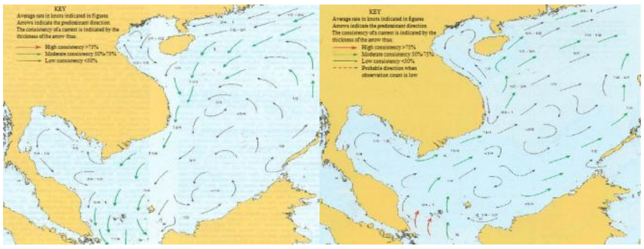

Fig. 3. Predominant surface currents in the South China Sea (left) during January (Northeast Monsoon) and (right) during July (Southwest Monsoon). Source: Admiralty Charts and Publications.

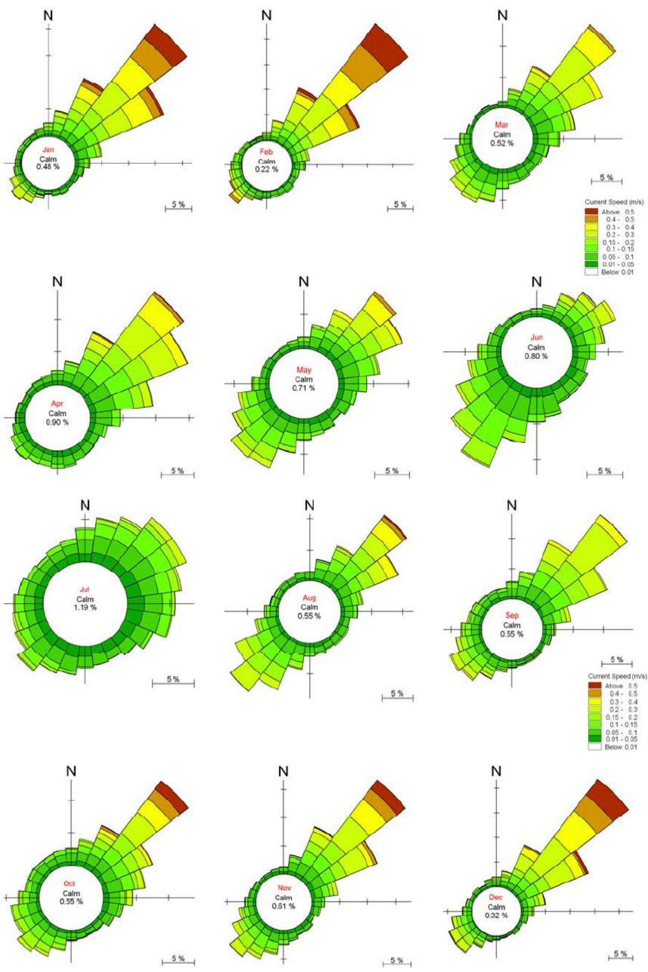

Fig. 4. Monthly current roses derived on the basis of current measurements at Kebabangan (see KBB in Fig. 1) for the period 1994 to 1999.

Fig. 4 provides monthly current roses derived on the basis of current measurements at Kebabangan (Fig. 1) for the period 1994 to 1999 [1]. The annual predominant current flow along the northeast direction is obvious, which is further indicated in Table I that provides percentage distribution of annually averaged current velocities in the study area. Table II provides mean and maximum current speeds at various depths at Kimanis-2 (K2), located just outside the Kimanis Bay entrance. The current velocity at Kimanis-2 is used in this study as the two study sites are close to Kimanis-2.

TABLE I: PERCENTAGE DISTRIBUTION OF ANNUALLY-AVERAGED CURRENT VELOCITIES IN THE STUDY AREA

All Year		Direction (45° Sector)							
		N	NE	E	SE	S	SW	W	NW
Current Speed (m/s)	0.05	4.37%	7.52%	6.70%	4.56%	5.21%	5.72%	4.13%	3.17%
	0.15	2.73%	12.26%	3.99%	0.62%	2.23%	7.89%	2.93%	1.01%
	0.25	0.39%	10.07%	0.74%	–	0.17%	2.51%	0.48%	0.01%
	0.35	0.03%	5.80%	0.05%	–	0.02%	0.24%	0.02%	–
	0.45	–	2.54%	–	–	–	0.07%	–	–
	0.55	–	1.20%	–	–	–	–	–	–
	0.65	–	0.44%	–	–	–	–	–	–
	0.75	–	0.08%	–	–	–	–	–	–
	0.85	–	0.07%	–	–	–	–	–	–
	0.95	–	0.02%	–	–	–	–	–	–

TABLE II: MEAN AND MAXIMUM CURRENT SPEEDS AT VARIOUS DEPTHS AT KIMANIS-2, AT KIMANIS BAY MOUTH (SEE FIG. 1 FOR LOCATION)

Depth (m)	Mean Speed (m/s)	Max Speed (m/s)	Std Dev (m/s)
Average	*0.16*	*0.58*	*0.10*
-2	0.24	0.80	0.13
-3	0.23	0.75	0.13
-4	0.21	0.74	0.12
-5	0.19	0.67	0.11
-6	0.18	0.61	0.10
-7	0.16	0.54	0.09
-8	0.14	0.51	0.08
-9	0.12	0.50	0.07
-10	0.10	0.16	0.05

TABLE III: DRILL CUTTING DISCHARGE VOLUMES, DURATIONS AND RATES FOR B-1 AND Z-1

Section (inch)	Discharge Volume (m^3)		Discharge Duration (hr)		Discharge Rate (kg/s)	
	Z-1	B-1	Z-1	B-1	Z-1	B-1
17 ½	46	46	9	9	3.41	3.41
12 ½	48	81	13	42	2.46	1.29
8 ½	14	14	10	10	0.93	0.93

II. DRILL CUTTINGS INPUT DATA

Table III provides cuttings volumes and disposal schedules for B-1 and Z-1, from which the drill cutting discharge rates (kg/s) may be computed. For Z-1, the total volume drilled is 108 m^3, contributing to a total mass of 259, 200 kg; while for B-1 the total volume is 141 m^3, contributing to a total mass of 338, 400 kg. It is assumed that 1 m^3 of drill cuttings has mass of 2400 kg. The highest cuttings discharge rates are 3.41 kg/s (during the drilling of the 17.5 inch section) for both Z-1 and B-1. Based upon drill cuttings size distribution, 50 % of drill cuttings consists of very fine particles that float in the water column as Suspended Solids (SS); while the remaining 50 % are larger particles that quickly settle onto the seabed to form piles. Particles of different sizes settle at different rates. For the simulation of sediment formation on the seabed, these larger particles are classified into ten (10) size classes, with ten (10) different settling velocities, as indicated in Table IV. These particle settling velocities will be used in pile height (sediment thickness) simulation in this study, the results of which will be presented in the following sections.

TABLE IV: DRILL CUTTINGS PARTICLE DIAMETER, DENSITY AND SETTLING VELOCITY DISTRIBUTIONS

Class	Diameter (mm)	Weight (%)	Density (ton/m^3)	Velocity (m/s)	Velocity (m/d)
1	0.007	10	2.4	1.90×10^{-5}	1.7
2	0.015	10	2.4	8.80×10^{-5}	7.6
3	0.025	10	2.4	2.50×10^{-4}	21.2
4	0.035	10	2.4	4.80×10^{-4}	41.6
5	0.05	10	2.4	9.80×10^{-4}	84.9
6	0.075	10	2.4	2.20×10^{-3}	191
7	0.2	10	2.4	1.60×10^{-2}	1356.5
8	0.6	10	2.4	5.70×10^{-2}	4898.9
9	3	10	2.4	2.10×10^{-1}	17988.5
10	7	10	2.4	3.20×10^{-1}	27483.8
	Sum	100			

III. PILE FORMATION SIMULATION

In this section, we present simulation results regarding the pile formation on the seabed due to the settling of discharged drill cuttings based upon current regimes as summarized in Table I, in which the current directions are grouped into eight sectors of 45° each. It should be noted that the total quantity of cuttings released (108 m^3 for Z-1 and 141 m^3 for B-1) is very small in the open sea. Details on the mathematical formulation and algorithm for simulating the settling of drill cuttings onto seabed are available elsewhere [4], [5]. Two hydrodynamic scenarios in the study site will be used for the simulations. First, to provide a worst-case scenario, calm sea conditions with no residual tidal current flows given by 0.0 sin (σt) m/s but with eddy dispersions will be used. Second, to reflect average tidal regimes in the study area, a mean tidal condition with a tidal velocity profile given by 0.2 sin (σt) m/s coupled with eddy dispersions is used. Higher tidal velocities will provide better dispersion and dilution of settling particles, and will reduce sedimentation impact on corals. This simulation result with higher tidal velocity will not be presented.

IV. Z-1 SIMULATION RESULTS

A. *Pile Formation for Z-1: Current of 0.2 Sin (σt) m/s*

Fig. 5 shows simulated cuttings distribution on seabed for Z-1 with mean current flow given by 0.2 sin (σt) m/s, where the frequency σ is chosen to fit the semi-diurnal tide with period of 12.42 hours. This mean current speed of 0.2 m/s is chosen to coincide with the mean tidal speed of about 0.2 m/s as given in Table II for Kimanis-2, located near to both Z-1 and B-1. Stronger tidal current flows exceeding 0.2 m/s would result in more spreading of the settling cuttings, giving rise to lower sediment thickness (mm), lower sedimentation rate (mg/cm^2/day) and hence lower adverse impacts. The results of which will therefore not be presented in this paper. On the other hand, weaker tidal flows (velocity = 0.0 sin (σt) m/s) will result in higher sediment thickness, higher sedimentation rate and hence higher adverse impact. The simulation results for this weaker tidal flows with no residual flow (u = 0.0 sin (σt) m/s) will be reported in this paper. The directions of the currents are oriented precisely according to the percentage distribution of current directions in the study site as given in Table I to statistically reflect the current regimes in the study area. As may be seen in Fig. 5, the pile formations do indeed reflect the predominant orientations of the current flows. It is obvious that the pile formations are located at a significant distance away from the coral sites, located at a distance of 500 m from the cuttings release. This has the implication that the pile thickness at the coral sites will be very thin and very insignificant (in fact pile thickness is 0.0 mm). Fig. 6 shows the zoom-in simulated 3-D cuttings distribution on seabed for Z-1 with mean flow of 0.2 sin (σt) m/s. The northeast orientation of the pile formation is obvious from these two figures. Further, the two figures demonstrate the presence of eight (8) rose configuration of the pile formation. The 8-sector pile formation helps to spread out the thickness of the pile.

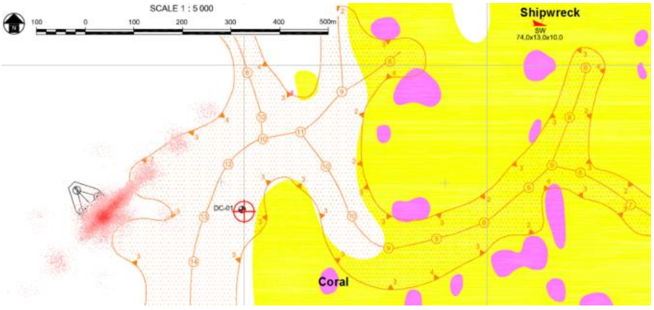

Fig. 5. Simulated cuttings distribution on seabed for Z-1 with mean flow of 0.2 sin (σt) m/s.

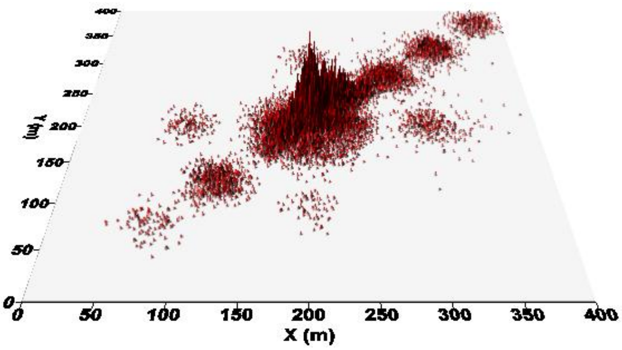

Fig. 6. Zoom-in simulated 3-D cuttings distribution on seabed for Z-1 with mean flow of 0.2 sin (σt) m/s.

B. *Sediment Thickness at Z-1: Current of 0.2 Sin (σt) m/s*

Fig. 7 shows the simulated sediment thickness distribution on the seabed along the predominant current flow direction of northeast for Z-1 with mean flow of 0.2 sin (σt) m/s. The maximum sediment thickness directly below the cuttings release site is 8 mm or 0.008 m. The sediment thickness falls quickly to very low values after a horizontal travel distance of 250 m along the predominant northeast flow direction. Hence the sediment thickness is 0.0 mm at the coral site and at the shipwreck site, as no particle will settle at either site located 500 m and 1000 m away respectively. Fig. 8 shows the simulated sediment thickness distribution on the seabed along NW-SE axis (perpendicular to the predominant flow direction) for Z-1 with mean flow of 0.2 sin (σt) m/s. All particles settle within a horizontal travel distance of 75 m along this NW-SE axis, with sediment thickness reducing quickly to zero after a horizontal travel distance of 75 m.

In conclusion, the sediment thickness at both the coral site and the shipwreck site is 0.0 mm, indicating no adverse impact on the environment at both sites.

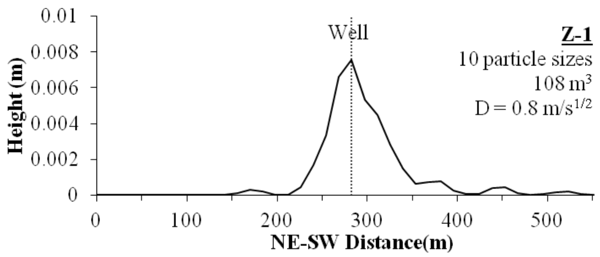

Fig. 7. Simulated sediment thickness distribution along NE-SW axis for Z-1 with mean flow of 0.2 sin (σt) m/s, showing maximum sediment thickness of 0.008 m below well.

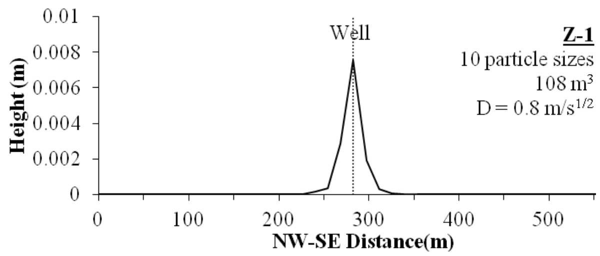

Fig. 8. Simulated sediment thickness distribution along NW-SE axis for Z-1 with mean flow of 0.2 sin (σt) m/s, showing maximum sediment thickness of 0.008 m below well.

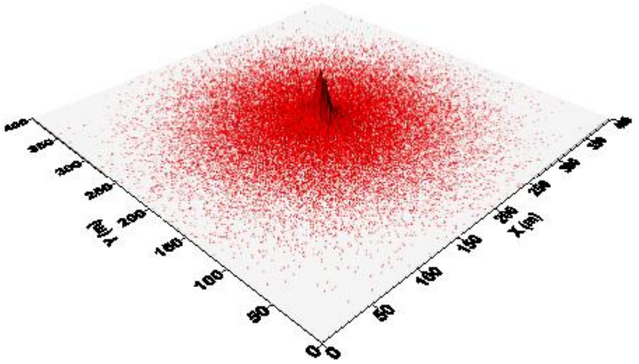

Fig. 9. Zoom-in simulated 3-D cuttings distribution on seabed for Z-1 with tidal current given by 0.0 sin (σt) m/s.

C. Pile Formation and Sediment Thickness for Z-1: Current of 0.0 Sin (σt) m/s

Under neap tide conditions, tidal currents are weak and flow in a random direction. Under this condition, it is appropriate to prescribe tidal current given by 0.0 sin (σt) m/s with eddy dispersion given by E m^2/s. The particles are carried by the eddy dispersion in a random manner, resulting in circular pile formation on the seabed. Fig. 9 demonstrates the zoom-in simulated 3-D pile distribution (circular pattern) on seabed for Z-1 with current given by 0.0 sin (σt) m/s and with eddy dispersion given by E = 0.64 m^2/s. All particles settle within a circle of radius 200 m, indicating the maximum horizontal travel distance of 200 m. The settled particles never reach the coral sites nor the shipwreck located 500 m and 1000 m away respectively. This means that the sediment thickness at the coral site and at the shipwreck site is 0.0 mm.

Fig. 10 shows simulated sediment thickness distribution along the axis from the cuttings release site (well) to the coral for Z-1, showing maximum sediment thickness of 0.03 m (30 mm) below the well and 0.00 m (0.0 mm) at the coral site. Fig. 11 shows simulated sediment thickness distribution along the axis from the cuttings release site (well) to the shipwreck site for Z-1, showing maximum sediment thickness of 0.03 m (30 mm) below the well and 0.00 m (0.0 mm) at the shipwreck site. In conclusion, the sediment thickness is 0.0 mm at both the coral and at the shipwreck, indicating no adverse impact on the environment and ecosystem at both sites.

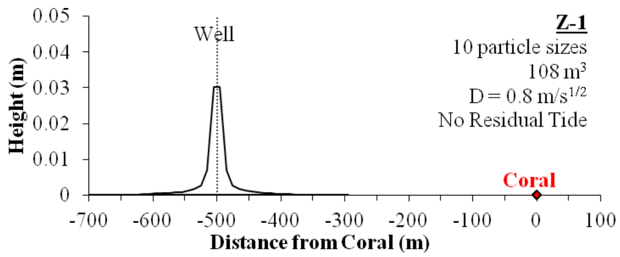

Fig. 10. Simulated sediment thickness distribution along the axis from well to coral for Z-1 with no residual flow, showing maximum sediment thickness of 0.03 m below well and 0.00 m at coral.

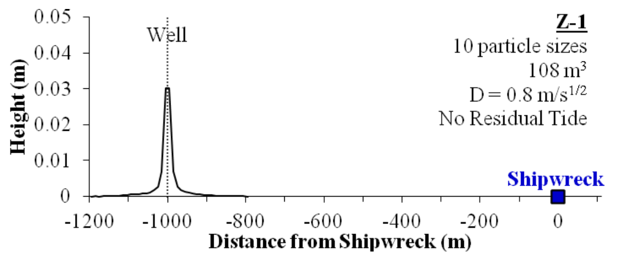

Fig. 11. Simulated sediment thickness distribution along the axis from well to shipwreck for Z-1 with no residual flow, showing maximum sediment thickness of 0.03 m below well and 0.00 m at shipwreck.

V. B-1 Simulation Results

A. Pile Formation for B-1 with Current of 0.2 Sin (σt) m/s

Fig. 12 shows the zoom-in simulated 3-D cuttings distribution on seabed for B-1 with mean tidal low of 0.2 sin (σt) m/s. The 8-rose pattern of the pile formation is clearly seen, reflecting the 8-sector pattern of current flow directions.

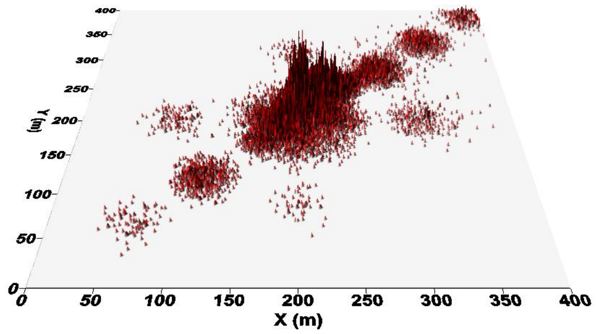

Fig. 12. Zoom-in simulated 3-D cuttings distribution on seabed for B-1 with mean flow of 0.2 sin (σt) m/s.

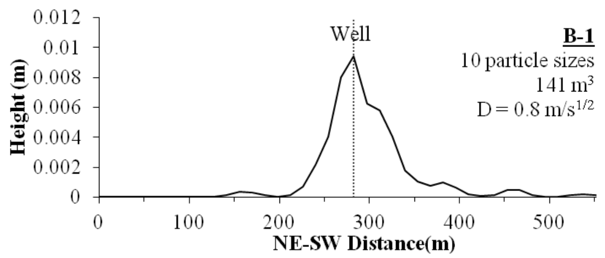

Fig. 13. Simulated sediment thickness distribution along NE-SW axis for B-1 with mean flow of 0.2 sin (σt) m/s, showing maximum sediment thickness of 0.01 m below well.

B. Sediment Thickness at B-1: Current of 0.2 Sin (σt) m/s

Fig. 13 and Fig. 14 depict simulated sediment thickness along the NE-SW axis and NW-SE axis respectively for B-1 with mean tidal current given by 0.2 sin (σt) m/s. The maximum sediment thickness is 0.01 m or 10 mm, located directly below the cuttings release site (well). Sediment thickness drops in value more quickly along the NW-SE direction as compared to that in the NE-SW direction.

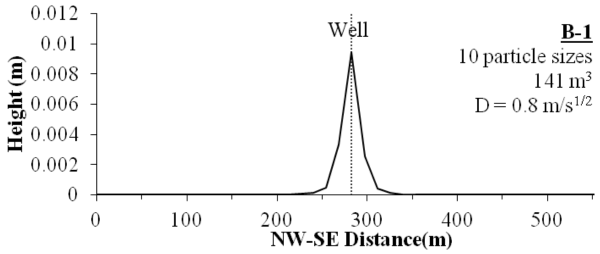

Fig. 14. Simulated sediment thickness distribution along NW-SE axis for B-1 with mean flow of 0.2 sin (σt) m/s, showing maximum sediment thickness of 0.01 m below well.

Fig. 15 shows simulated sediment thickness along the axis from cuttings release site to the coral for B-1 with mean tidal current of 0.2 sin (σt) m/s. The sediment thickness is 0.01 m (10 mm) below the well. At the coral site located at least 100 m away, the sediment thickness drops to 0.00005 m (0.05 mm). This small sediment thickness of 0.05 mm is deemed insignificant, particularly as the sedimentation takes place over a short duration of 3.875 days. As will be demonstrated in subsequent sections, this sediment thickness of 0.05 mm is equivalent to a sedimentation rate of 3.1 mg/cm^2/day. We will show in later sections that this sediment thickness of 0.05 mm and sedimentation rate of 3.1 mg/cm^2/day are insignificant to pose any impacts on the corals.

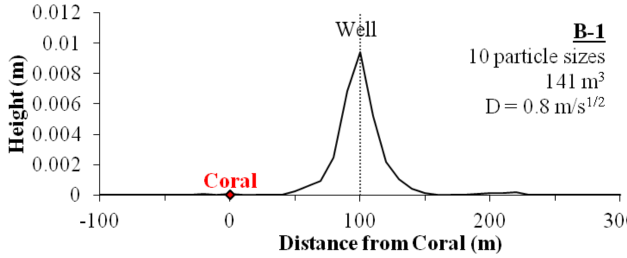

Fig. 15. Simulated sediment thickness distribution along well to coral axis for B-1 with mean flow of 0.2 sin (σt) m/s, showing maximum sediment thickness of 0.01 m below well and 0.00005 m at corals.

C. Pile Formation and Sediment Thickness for B-1: Current of 0.0 Sin (σt) m/s

Under this condition, the particles are carried by the eddy dispersion in a random manner, resulting in circular pile formation on the seabed, similar to the formation pattern displayed in Fig. 9. Fig. 16 depicts simulated sediment thickness distribution on the seabed along the axis from the cuttings release site (well) to the coral site for B-1 with current of 0.0 sin (σt) m/s. The maximum sediment thickness is 0.04 m or 40 mm located directly under the well. Ninety percent of particles settled within a radius of 25 m. At the coral site located at a distance of more than 100 m away from well, the sediment thickness is only 0.0005 m or 0.5 mm. This sediment thickness of 0.5 mm is equivalent to a sedimentation rate of 31 mg/cm^2/day. This small sediment thickness and sedimentation rate is considered insignificant, as the sedimentation takes place over a short duration of 3.875 days. We will deliberate more on this in the following sections.

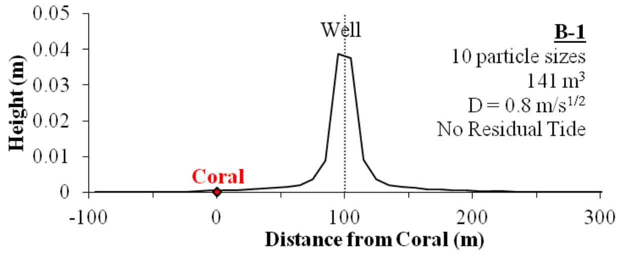

Fig. 16. Simulated sediment thickness distribution on seabed along the axis from coral to well for B-1 with no residual flow, indicating sediment thickness of 0.04 m below well and 0.0005 m at the corals.

VI. Are Corals Resilient

It is noted that in most scientific literature discussing the impact of sedimentation on coral, two parameters are typically used. One parameter measures the sediment thickness (mm), while the second parameter measures the sedimentation rate (mg/cm^2/day). The sedimentation rate mg/cm^2/day measures the mass (mg) of sediment that settle over an area 1 cm^2 in 1 day. For example, a sedimentation rate of 10 mg/cm^2/day means that a total of 10 mg of sediment settle over an area of 1 cm^2 in 1 day. We first demonstrate the conversion from sediment thickness (mm) into sedimentation rate (mg/cm^2/day). We show how to convert 0.05 mm of sediment thickness accumulated over a duration of 3.875 days into sedimentation rate of 3.1 mg/cm^2/day. A sediment thickness of 0.05 mm (0.005 cm) over an area of 1 cm^2 has a volume of 0.005 cm^3. With a density of 2.4 g/cm^3, the mass of this volume is equal to 0.012 g or 12 mg. This means that the total mass of sediment that settles over an area of 1 cm^2 is 12 mg, implying a sedimentation value of 12 mg/cm^2. From Table III, we note that the entire discharge operation take place over a duration of 93 hours or 3.875 days. Hence the sedimentation rate is 12 mg/cm^2/3.875 days = 3.1 mg/cm^2/day. Similarly a sediment thickness of 0.5 mm accumulated over 3.875 days is equivalent to a sedimentation rate of 31 mg/cm^2/day. We will show in the following sections that these set of sediment thickness and sedimentation rates is insignificant in posing any adverse impact on the corals by comparing these values to those cited in the literature.

A. Tolerance of Corals to Sedimentation: Intensity, Duration and Frequency

It should be noted that many studies conducted to understand corals tolerance to sediments have demonstrated that some corals can indeed survive well in turbid environments laden with sediments [6]–[9]. These and other studies have demonstrated the occurrence of coral reefs, often with high live coral covers, in areas of high and fluctuating Suspended Solids (SS), turbidity and sedimentation, for example in the inner shelf of the Great Barrier Reef [10]–[13]. Net deposition rates in the nearshore coral settings on the inner shelf of the central Great Barrier Reef (GBR), averaged 3 to 7 mg/cm^2/day over the course of a year [14]. But sedimentation rates in excess of 200 mg/cm^2/day for periods of days to weeks are not uncommon on fringing reefs of the GBR. Near-shore fringing reefs in the Great Barrier Reef region that are characterized by high and variable sedimentation rates, from 2 to 900 mg/cm^2/day (short-term rates) with long-term means of 50 to 110 mg/cm^2/day, were found to sustain highly diverse coral growth with a mean coral cover of 40–60% [15]. A few coral species, such as Montastraea cavernosa and Astrangia poculata, can tolerate sedimentation rates as high as 600 to 1380 mg/cm^2/day [16], [17].

Field and laboratory experiments in Florida (USA) have shown that some of the tolerant coral species in the Caribbean can survive complete burial with sediment for periods ranging from 7 to 15 days [18]. Sedimentation at the rate of 200 mg/cm^2/day lasting for 45 days has no effect on Acropora cervicornis [19], [20]. Further, sedimentation rate of 200 mg/cm^2/day for 6 continuous weeks have caused only minor tissue damage and bleaching for the species Sinularia dura, Gyrosmilia interrupta, Favites pentagona, Favia favus and Sinularia leptoclados [21], [22]. Rice and Hunter [18] noted that long-term exposure to elevated levels of SS (50 to 100 mg/l) and high levels of coral bed sediment (tens of mg/cm^2/day) can cause reduced coral growth and reduced reef development. However, recent studies indicate that the observed adverse impacts are often less severe than what had been previously reported. Further, recent studies from near-shore reefs in the Great Barrier Reef provide convincing evidence of spatially relevant and temporally persistent reef-building having occurred over millennial timescales [12], [13].

In a study conducted in Tanzania over a two-year period from October 2006 to March 2009, monthly sedimentation rate monitored ranged from 0.2 to 41.5 mg/cm^2/day at the Bawe reefs, and from 0.8 to 65.8 mg/cm^2/day at the Chumbe reefs, with both sites having high live coral covers and high coral genera diversity [23]. This suggests that corals at Chumbe and Bawe have probably adapted to the sedimentation situation and thus are able to overcome the sediment lethal limit of 10 mg/cm^2/day suggested by Rogers [19]. The current threshold level for sediment thickness adopted for the Norwegian Continental Shelf in environmental risk assessment models by the offshore industry is 6.3 mm thickness. Mimicking a typical drilling event in an experimental study, L. pertusa was exposed to doses of fine-grained drill cuttings (less than 63 µm) over 3 weeks to reach total sediment thicknesses of either 6.3 mm (1×) or 19 mm (3×), corresponding to average daily doses of ca. 65 and 195 mg/cm^2/day respectively. The number of fragments with smothered tissue in the 6.3 mm treatment was significant. The number of coral fragments with smothered tissues and polyp mortality increased with higher sediment load of 19 mm [24]. It can be concluded that a 3-week burial by drill cuttings at the threshold level of 6.3 mm currently adopted in environmental risk assessment models may result in damage to L. pertusa. However, the simulated sediment thickness of between 0.05 mm to 0.5 mm over an exposure period of 3.875 days for this study is relatively low. In another repeated exposure study, L. pertusa was exposed to 33 mg/cm^2 every second day for 45 days, corresponding to a sedimentation rate of 16.5 mg/cm^2/day, without showing any signs of exhaustion of sediment rejection mechanisms, suggesting that sediment rejection in L. pertusa is rather efficient.

Perry and Smithers [9] observe that corals can indeed survive well in turbid environment with high SS and high sedimentation. Five species of gorgonians in the highly sedimented waters of Singapore showed growth rates ranging from 2.3 to 7.9 cm/yr, which are comparable to published growth rates from non-sedimented environments [25]. The reason for the observed growth rate despite high SS and high sedimentation could be due to flushing by tidal currents that can efficiently remove sediments from corals [13], [26]. This efficient removal of sediments from corals by tidal flushing is applicable to the present study sites, which are located in areas with good tidal flushing augmented by waves and internal eddies [1]. Corals that are naturally exposed to and adapted to high and variable background conditions of SS, turbidity and sedimentation (e.g. due to tides, storms and/or monsoon, as is the case with the study site) will have higher tolerances to short-term pulses in SS, turbidity or sedimentation caused by dredging or drilling operations [27]. This remark certainly applies to the study sites.

B. Conclusion: Sedimentation at Coral Sites Is Low

Tolerance of coral to sedimentation and water-column SS is related to the intensity, duration and frequency of exposure [28]. Scientific literature derived from field-based and laboratory studies have provided some guidelines regarding the tolerance of coral reef systems to SS and sedimentation. Quantitative regulatory framework regarding critical thresholds is, however, yet to be formulated, as most research on tolerance of corals to SS or sedimentation is rarely quantified. It should be appreciated that over half of coral reef complexes are made up of sediments [29], suggesting that corals and sediments do co-exist in a natural environment due to natural adaptation over time. Corals can withstand a certain amount of settling sediment, as this occurs naturally, allowing the coral communities to adapt [9], [19], [30]. Several studies revealed that many coral species and reefs are capable of surviving sedimentation rates of 100 mg/cm^2/day for several days to several weeks without any major negative effects; while some (nearshore) reefs naturally experience sedimentation rates well over 200 mg/cm^2/day. Long-term maximum sedimentation rates that can be tolerated by different corals have been reported in the literature to range from 10 mg/cm^2/day to over 400 mg/cm^2/day. Sedimentation rate is usually highest on inshore reefs as well as in reef systems that are sheltered from wave; but decreases with distance from shore and with increasing exposure to wave energy [31]. The study sites are located in areas that may be termed in-between. Hence the long-term sedimentation rates that can be tolerated by corals in the study sites may well be in the range of about 100 mg/cm^2/day. Short-term (2 to 3 days) sedimentation rates that can be tolerated by corals in the study sites could be in the range exceeding 100 mg/cm^2/day.

This wide range of tolerance limits suggests that different coral species and corals in different geographic regions may respond efficiently to increased amounts and rates of sedimentation due to evolutional adaptation. The met-ocean regimes (tides, waves, monsoons) in the study sites of Z-1 and B-1 suggest that the natural background sedimentation rates may be modestly high during the episodic but regular occurrences of storms and monsoons that can re-suspend sediments. The coral communities probably have adapted to periodic high sedimentation rates over short durations. These evolutional adaptations have provided the corals with the ability to tolerate minor pulses in sedimentation at B-1 and Z-1, as predicted by model simulation in this study, over a short duration of 3.875 days, arising from the drilling operation.

For B-1, the sediment thickness over the corals subject to the mean tidal condition with current velocity of 0.2 sin (σt) m/s is 0.05 mm. This sediment thickness of 0.05 mm, as shown earlier, is equivalent to a sedimentation rate of 3.1 mg/cm^2/day. Compared to the sedimentation rates that can be tolerated by corals cited above (long-term exposure to between 10 mg/cm^2/day and over 400 mg/cm^2/day), the intensity of exposure to this sedimentation rate of 3.1 mg/cm^2/day is indeed low. Moreover, this low exposure intensity occurs only once over a short duration of 3.875 days. Exposure to low intensity of sedimentation over a short duration for one time only (in-frequent) means that the impacts on the corals is therefore insignificant. The maximum sediment thickness of 0.5 mm over the corals at B-1 is less than one tenth of the sediment threshold of 6.3 mm suggested by Rogers [19]. Therefore, this exposure to moderate sedimentation intensity of 31 mg/cm^2/day over a short duration of 3.875 days is also not likely to pose severe impacts to corals. Nevertheless it is prudent to exercise caution during the well drilling at B-1 to keep the well drilling site sufficiently far away from the corals, at least 100 m preferably 200 m, at the low volume of drilling (141 m^3) in site B-1. For site Z-1, which is located at a distance of 500 m away from the corals, the impact of sedimentation due to drill cutting is highly insignificant, because of the low volume of drilling (108 m^3) and sufficient distance from the corals.

VII. Conclusion

The settling and dispersion patterns of drill cuttings are sensitive to settling velocity of the particles, to tidal currents and to coastal diffusion, all of which are variable. As a consequence, all simulation results obtained for this study are sensitive to settling velocity, as well as to the ambient marine environment. Current measurements near the study site are made available for the period 1994 to 1999. Dispersion coefficient value for the study area is around 0.5 to 1.0 $m^{2/}$s, which is consistent with those estimated based upon previous relevant studies [32]-[34]. Sensitivity analysis simulations are performed by varying the tidal currents and coastal diffusion within a reasonable range around values indicated above. This sensitivity analysis yielded similar conclusion that the release of drill cuttings at the low rates used in this study will not pose significant impacts on the corals.

Corals differ greatly in their ability to resist sedimentation, through a variety of mechanisms, often assisted by tidal currents that clean off sediments settled on coral tissues, at the expense of metabolic energy. There is little information in the public literature about the conditions that can occur in situ during dredging or drilling around coral reefs. Much less is known about the biological/ecological response and adaptation of corals to sediments created by these operations. This is an area worthy of intensive research in assessing the impacts of drill cuttings on coral health.

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S. Y. Teh was born on Nov. 5, 1981 in Kedah, Malaysia. She received her BSc, MSc and PhD in mathematical modeling in 2004, 2005 and 2008 respectively, all from Universiti Sains Malaysia.

In 2006, she was awarded the UNESCO/Keizo Obuchi Research Fellowship to undertake research on "Management Modeling of Everglades Wetlands Hydrology and Ecosystems" at University of Miami. Since then, she has been invited to University of Miami and Nanjing Forestry University under USGS grants and to four workshops at Abdus Salam International Centre for Theoretical Physics (ICTP)at Trieste, Italy under the sponsorship of ICTP. She is currently an Associate Professor at School of Mathematical Sciences, Universiti Sains Malaysia. She works on various topics in ecosystem and environmental modelling, many of which were initiated and driven by the needs of the country or industry. Her research interests revolve around mathematical modelling with particular focus on computational simulation of real-life problems to provide insights and to suggest possible solutions.

Dr. Teh has many articles published in Journal of Asian Earth Sciences, Ecosystems, Ecological Modelling, Landscape Ecology and Agricultural and Forest Meteorology

H. L. Koh was born on May 30, 1948 in Penang, Malaysia. He received his BSc from University of Malaya in 1970 and MA as well as the PhD in mathematics in 1971 and 1976 respectively from University of Wisconsin, Madison, USA.

He was the recipient of Oppenheim Prize of University of Malaysia and Fulbright Scholarship USA and DAAD Fellowship. He served as an Associate Member of the International Centre for Theoretical Physics (ICTP) from 1986 to 1992. He is currently a Professor at Sunway University Business School. He has served for 40 years in Universiti Sains Malaysia before continuing his research at Sunway University. His fields of specialization include environmental and ecological system modelling and simulations, integrated river basin management and modeling, numerical modeling of tsunami hazards and numerical simulation of dengue and H1N1 epidemics.

Prof. Koh has many journal publications, notably in Water Sciences & Technology, Environmental Monitoring and Assessment, Water Quality Research Journal of Canada, Pollution in the Urban Environment, Journal of Asian Earth Sciences, Ecosystems, Ecological Modelling, Landscape Ecology and Agricultural and Forest Meteorology.