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Assessment of Factors Affecting Dredged Volume Estimation in Hydrographic Survey Applications: Case Study of New Suez Canal

تقييم العوامل المؤثرة على الكميات التقديرية لعمليات التكريك: حالة دراسية لقناة السويس الجديدة

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KEYWORDS:
Volume Computations, Single-Beam Survey, Quality Control, Quality Assurance, Civil 3D, ARC GIS, New Suez Canal

الملخص العربي: **وقد تم اختبار تأثير تلك العوامل أثناء معالجة البيانات باستخدام ثلاث برامج مختلفة. وأظهرت النتا:- الدقة العالية في مسح الأعماق البحرية أمر لا غنى عنه في مشاريع التكريك لأن لها تأثيراً مباشرا على كميات الحفر تحت المياه وبالتالى تؤثر على تكلفة المشروع. في هذا البحث تم دراسة العوامل المختلفة المصاحبة لاعمال الرفع المساحي البحري و التي تؤثر في حساب كميات الحفر فى عمليات التكريك. وقد استخدمت البيانات الناتجة من عمل سونار ذات شعاع واحد بعد تعميق وتوسيع البحيرات المرة الكبرى في مشروع قناة السويس الجديدة، الذي تم حديثا في مصر.**

حركة القارب وطريقة معالجة البيانات من العوامل تؤثر على دقة اعمال الرفع المساحي البحري و بالتالي على كميات الحفر اثناء التكريك ئج أن نتيجة لهدوء سطح المياه في قناة السويس فى بعض الاماكن تكون فيها الحركة الرأسية و الافقية و الدورانية,للمركب غير مؤثر بشكل فعال فى حساب حجم الحفر. وقد ثبت أن كثافة البيانات (تباعد الخطوط) لها تأثير واضح على دقة البيانات، حيث كلما قلت تباعد الخطوط (زيادة كثافة البيانات) كلما انخفضت نسبة الخطأ . وكذلك قد وجد أن إستخدام برامج تستخدم النماذج الرقمية لطبوغرافية القاع بطرق مختلفة تسبب فى تغيرات فى حساب كميات الحفر الناتجة من عمليات التكريك.

Abstract— **An accurate bathymetric survey is a principal issue in dredging projects because it has a direct impact on the estimated dredging quantities, project process and cost. In this research, various factors affecting the accuracy of bathymetric survey and hence dredging volume quantities have been investigated. The data obtained from single-beam echo sounder surveys after the deepening and widening of Great Bitter Lakes in the New Suez Canal project, which was recently carried out in Egypt, have been used. The ship motion, data density, and processing software are the factors investigated that affect the accuracy of bathymetric survey. The effect of those factors had been tested during data processing using different hydrographic software packages. Results showed that due to the calm surface in Suez Canal during the survey, heave, pitch and roll effects are insignificant in volume computations. It has been proved that data density (line spacing) has an influential effect on volume estimation, where the closer the line spacing (increased data density), the lower the uncertainty. It has been also found that using different volume calculation software based on different Digital Terrain models may cause differences in the resulting estimated volume.**

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I. INTRODUCTION

HYDROGRAPHIC survey is a branch of surveying which involves the measurement of water depth, description of submerged features, characteristics of tides, currents and waves, and the physical and chemical properties of the water. These measurements are of great importance for many applications such as navigation, construction of marine structures, offshore oil exploration and the determination of shoreline. Reference [3] said that Bathymetry is part of hydrographic survey which covers the measurement of water depth in areas covered with water such as oceans, rivers and lakes.

Depth measurements have many potential uncertainty compositions. These components include the measurement method, sea state, water temperature and salinity, transducer beam width, bottom irregularity and consistency, and vessel heave-pitch-roll motions. In addition, the depth must be referenced to the local water surface that is referenced to a datum plane at some remote point.

Depths are normally measured using either single-beam or multi-beam echo-sounding systems. SBES (Single-Beam System) is still the most common tool used in ports and harbors survey and will continue to give valid results when used correctly in a well planned and executed survey. The SBES, as soundings, are only acquired directly underneath the transducer. Survey lines run perpendicular to the underwater slopes and the line spacing between the survey lines is dependent on the scale of the final product and the required resolution. Tie lines (longitudinal lines) are run perpendicular to the primary survey lines but at wider spacing and act as a quality assurance check on the acquired field data as shown in Figure (1).

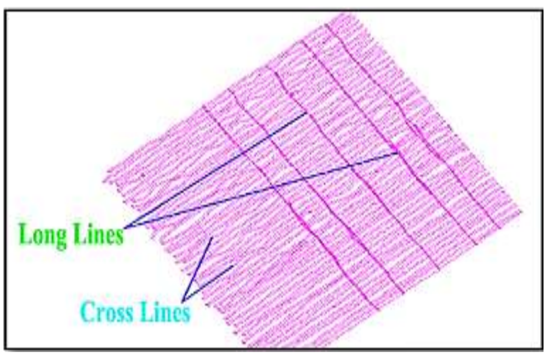

Figure 1: The Difference Between Crosslines and Longlines

The major disadvantage of SBES is that it illuminates only a narrow portion of the seafloor as shown in Figure (2). Also, the depths between survey lines will be omitted from the bathymetric data, while MBES (multi-beam system) can provide continuous coverage as shown in Figure (3).

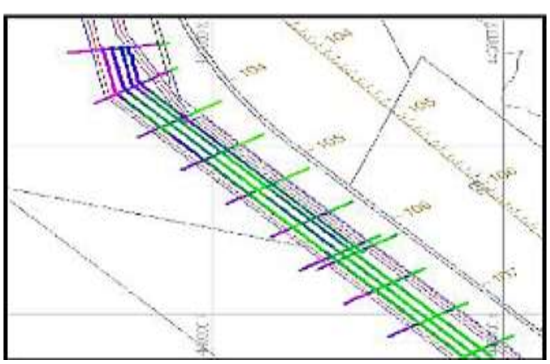

Figure 2: Single Beam Echo Sounder Survey Data

The aim of the current research work is to assess the effects of the following factors on the accuracy of the bathymetric survey data and hence the estimated dredged volumes:

- *Ship motion.*

The software package used to process the collected data. Heave is basically a function of wave swell and period. Heave errors are normally excessive at coastal entrances and on offshore approach channels. Modern heave compensators can effectively record heave movement and smooth out these effects. [8].

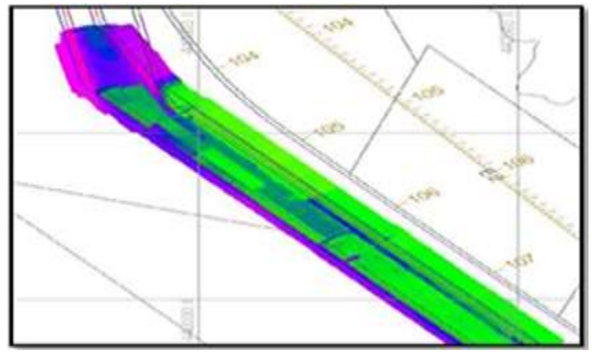

Figure 3: Multibeam Echo Sounder Survey Data

II. MATERIAL AND METHODS

Within this research, an investigation about the factors affecting volume estimation results from a hydrographic survey has been performed. This methodology studied the effect of motion sensors and software used concerning single-beam survey on volume calculations. Three test areas were selected in Great Bitter Lakes in Suez Canal to perform the investigations (figure 4) where the hydrographic survey had been carried by the Suez Canal authority in 2015.

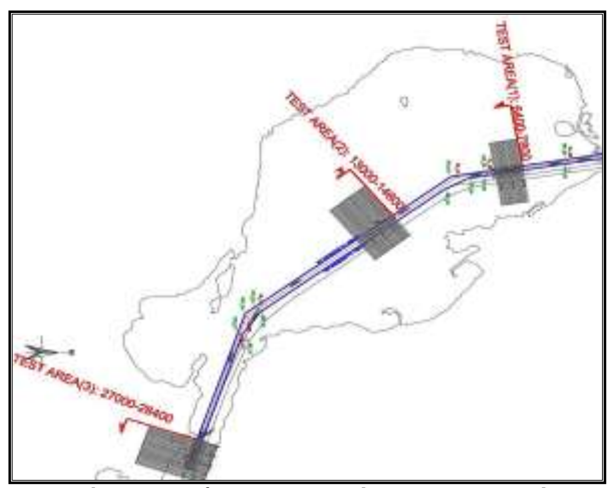

Figure 4:The position of test areas 1, 2 and 3 in new Suez Canal project

Main single-beam survey lines were perpendicular to the canal axis with a line spacing of 10 m and cross lines with a spacing of 45 m for data accuracy inspection.

Reference [10] said that Heave is one of the factors that did not mentioned by "IHO Standards for Hydrographic Survey, (2008)" to be measured in its specifications. They only mentioned that for Sweep Systems (multi-transducers arrays): "Once the heave on the transducers exceeds the maximum allowable value in the uncertainty budget, sounding operations should be discontinued until sea conditions improve".

III. Factors Affecting Dredged Quantities Estimation

A. Heave, roll, and pitch:

Reference [1] show that the hydrographic survey vessel shows three-dimensional movements due to environmental effects such as wind, current, other vessel wakes, etc. as shown in Figure (5). As a result, the vessel will experience pitch, roll and heave. These motions (if ignored) cause errors in depth and in the positioning of the sounding. The magnitude of the errors can reach up to even meters depending on the sea state, vessel size, vessel characteristics, and especially wave height. However, accurate and reliable depth and position data are needed in bathymetric charts prepared for shallow water navigation, dredging, various engineering applications, harbor maneuvers, and maximizing cargo capacity safely. Therefore, compensation of vessel motion is necessary for several applications.

Reference [10] shows that the impact of lateral vessel roll and pitch of the vessel are more pronounced when narrow-beam transducers are employed because the sounding cone becomes non-vertical and measures a longer slope distance. Up and down vertical heave is reflected in the wave height. Heave is superimposed with roll and pitch on the observed depth. The apparent smoothing of undulations on the graphical record is not always interpolated correctly, depending on the vessel's course relative to the sea, size, characteristics, and wave height. On an irregular bottom, it is extremely difficult to separate vessel motions from the bottom undulations. Digitally recorded depths do not allow for any human interpretation or smoothing of undulations due to heave, pitch, and roll.

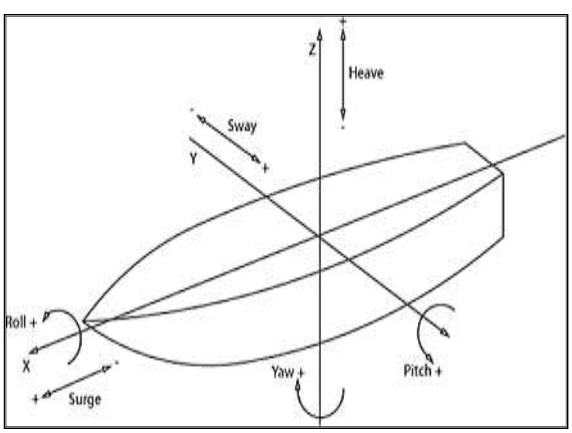

Figure 5: Heave, Pitch and Roll of Survey Vessel

B. Single-Beam and Multi-Beam Echo Sounders

Reference [5] shows that the Single-beam (SBS) and multi-beam (MBS) systems are reasonably accurate in seafloor mapping. The MBS system, however, offers better resolution and coverage and produces better classification accuracy than that of the single-beam can provide. Although closer track line spacing would have likely improved the accuracy of the SBS results, the distribution of backscatter characteristics for the different classes shows MBS to have considerably better discrimination than the data from SBS. As the costs associated with surveys are related predominantly to vessel time, the cost benefit of using MBS system with respect to ship time needed is considered to be an important factor when choosing a sonar system for seabed habitat mapping.

C. Software Package

The degree of uncertainty in the hydrographic data depends on the apparatus used, the accuracy of tide measurements, and the sea state at the time of the survey. Consequently, volume estimates are based on hydrographic data that includes some errors. There is also error associated with the different methods used to calculate volumes from the hydrographic data, including the cross-section method and the surface-to-surface TIN (Triangulated Irregular Network) method. The accuracy of the TIN method depends upon the density of the hydrographic data. Greater density allows better contouring of the surface and less error in volume estimates.

It is a common practice to use the Delaunay triangulation to construct a TIN rather than other, less restrictive triangulations. In a Delaunay triangulation, the circumscribing circle of any triangle contains no other vertices. [2]

In this research three 3D-software packages were used to calculate the estimated volume in the new Suez Canal Project, HYPACK, CIVIL 3D and ARC GIS. Hypack provided the surveyor with all of the tools needed to design the survey, collect, process, reduce data and generate final product. The other two programs were used to calculate volumes using the TIN method. A comparison was made between the volumes produced by the three programs. The results demonstrated that the Hypack package is better recommended for hydrographic data than any of the other software.

The accurate measurement of dredge production is essential for maintaining the maximum efficiency and cost effectiveness of the dredging process. The use of production measurement systems on pipeline and hopper dredges provides dredging personnel with tools for measuring and monitoring production quantities. The accuracy of these production monitoring systems varies according to the instrumentation used and the knowledge of the sediment and water properties associated with the dredging activity. [7]

IV. Hydrographic Survey for New Suez Canal

The International Hydrographic Organization (IHO) standards Special Publication No. 44, 5th Edition has been amended for recommended line spacing. They are uniform in that the Suez Canal can be classified as a Special Order so that there is no recommended maximum line spacing for single-beam, full sea-floor coverage.

A single-beam echo sounder type Odom Echo-trace MKIII high frequency 210 kHz was used with the HYPACK software package for data acquisition. Dredge surveys can be divided into three groups; pre-dredge, progress (interim), and post-dredge surveys. Pre-dredge surveys were performed before starting dredge works and were considered the initial survey data. For monthly payments, progress surveys were conducted to estimate the dredged volume. A post-dredge survey was accomplished after dredging had been completed in a specific location to ensure that all materials had been removed and that the required depths had been achieved.

V. EXPERIMENTAL WORK:

The single-beam survey data was acquired during the widening and deepening of Great Bitter Lakes in the Suez Canal. The first two tests areas were from Km 95 to Km 96 and from Km 113 to km 114 where the calm-sea state did not induce effects on single-beam data; the third test area was from Km 120 to Km 122 where reasonably a rough-sea state induced evident effects on single-beam data. The single-beam data was processed by applying heave, pitch and roll. TIN models were created based on single-beam cross lines and longitudinal lines. In order to compare the results a border was defined. The volume calculated inside the border based on the TIN model was referenced to Zero level. To study the effect of ship motion and hydrographic software on the measured depths and the estimated dredging quantities, three tests were performed on three different test areas. Ship motion investigations were performed by calculating the dredged volume through applying heave, pitch and roll effects in four different cases.

The software investigations were performed on computing the results by using three different 3D software packages, which were HYPACK, CIVIL 3D and ARC GIS.

A. Bathymetric Uncertainty Estimation

The International Hydrographic Organization (IHO) stated the Total vertical uncertainty (TVU) as “The component of uncertainty propagation, when all contributing measurement uncertainties, both random and systematic, have been included in the propagation within vertical dimension”

Recognizing that there are both constants and depth dependent uncertainties that affect the uncertainty of the depths, the formula below is to be used to compute, at the 95% confidence level, the maximum allowable TVU.

Reference [4] shows that the parameters “a” and “b” for each Order, as given in the Table, together with the depth “d” have to be introduced into the formula in order to calculate the maximum allowable TVU for a specific depth:

$$\mathrm{TVU} = \pm\sqrt{a^2 + (b * d)^2}$$

Where:

a Represents that portion of the uncertainty that does not vary with depth

b Is a coefficient which represents that portion of the uncertainty that varies with depth

d Is the depth

(b * d) Represents that portion of the uncertainty that varies with depth

TABLE 1
MINIMUM STANDARDS FOR HYDROGRAPHIC SURVEYS

Order	**Special order**
• *Maximum allowable TVU at 95%* • *Confidence level*	• a = 0.25 • b = 0.0075

Where the (95% confidence level) is the probability that the true value of a measurement will lie within the specified uncertainty from the measured value. It must be noted that confidence levels (e.g. 95%) depend on the assumed statistical distribution of the data and are calculated differently for 1 Dimensional (1D) quantity. In the context of this standard, which assumes Normal distribution of error, the 95% confidence level for 1D quantities (e.g. depth) is defined as (1.96 * standard deviation). [4]

Once Suez Canal is classified as special zone so the TVU (Total Vertical Uncertainty) for the research test areas equal

$$\mathrm{TVU} = \pm\sqrt{(0.25)^2 + (0.0075 * 24)^2} = 31\mathrm{cm}$$

It can be said that if the vertical uncertainty exceeds these results the survey must be stopped till the weather is improved.

VI. RESULTS

A. Ship Motion Measurement

The first two test areas’ results were similar so only one will be explained. The volume is calculated in four cases

- Case 1: Without any Effect
- Case 2: With Heave Effect
- Case 3: With Pitch and Roll Effect
- Case 4: With Heave, Pitch and Roll Effect

1. First Test Area (New Suez Canal)

In the first test area the effect of heave, pitch and roll on the measured depths is investigated separately. The test was on applied on One kilometer in great bitter lakes. The total number of points that the investigation run on were 19788 points. Figure 6 shows only heave correction values on the measured depths for a sample of 20 points in this area.

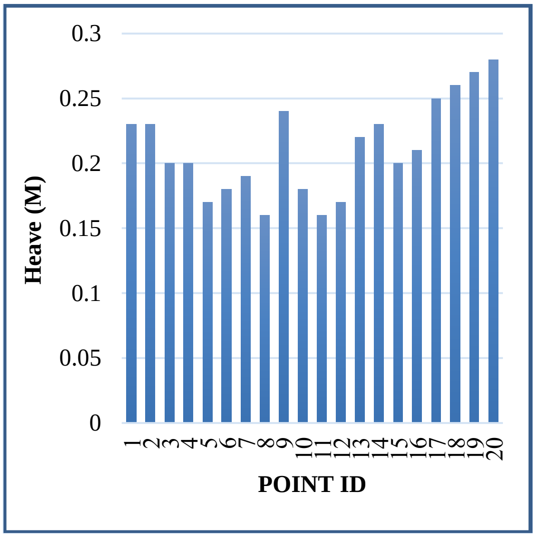

Figure 5: Data sample clarifying Heave Effect on Depths Readings in First Test Area

Figure 6 illustrates that first area in new Suez Canal has insignificant heave values which can barely affect the measured depths.

TABLE 2
THE STANDARD DEVIATION OF HEAVE CORRECTION

Min (m)	Max (m)	Mean (m)	Stand. deviation
-0.1	0.3	0.00053	0.0218

According to Table 2 the 95% confidence level for heave correction can be calculated for the whole data of the first test area from the above equation.

Conf. level = 1.96*STDV

=1.96*0.21834=0.042 m

So, the confidence level of heave correction is beyond the allowable uncertainty of the test area. The following figure explains pitch and roll values in the same area.

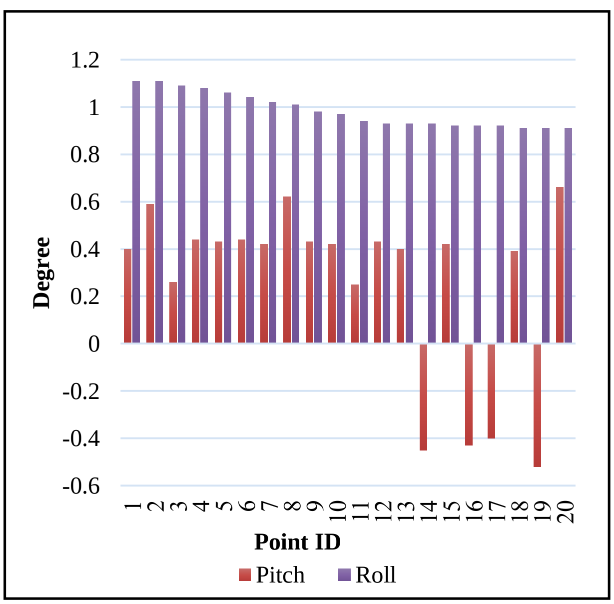

Figure 6: Pitch and Roll Values in the First Test Area

Figure 7 shows that pitch and roll have values ranges from -0.5 deg. To 1.2 deg. Which can be neglected when computing the estimated volume quantities as its effect on depths reading almost not exist.

TABLE 3
THE COMPLETE DATA OF PITCH AND ROLL EFFECT

Pitch(deg)		Roll(deg.)		Mean (m)	Stand. Dev.
min	max	min	max	-0.00056	0.022
-0.85	0.95	0	1.2		

According to Table 3 the 95% confidence level for pitch and roll correction can be calculated for the first test area from the above equation.

Conf. level = 1.96*STND =1.96*0.21834=0.0427 m

In this regard the confidence level of pitch and roll correction is also beyond the allowable vertical uncertainty of Suez Canal area.

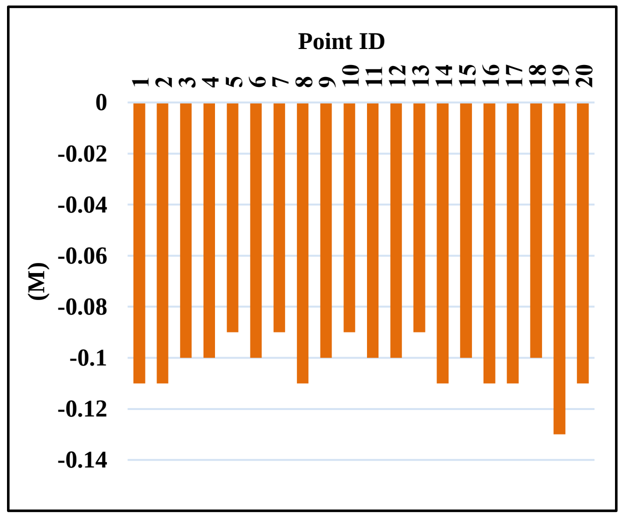

Figure 7: The difference induced by Pitch and Roll on Raw Depths in First Test Area

Figure (8) shows that the maximum difference between the measured depths and the corrected depths which induced by pitch and roll on the raw depths is 13 cm which can be neglected.

Table (4) shows the volume quantities in the first test area in great bitter lakes for four cases mentioned above.

TABLE 4
DIFFERENCES IN VOLUME QUANTITY DUE TO SHIP MOTION EFFECT

Cases	Volume Quantity (m^3)	Diff. (m^3)	Percent. (%)
Without any effect	2,190,435	263	0.012
With Heave effect	2,190,689	254	0.0004
With Pitch and Roll effect	2,190,456	242	0.011
With Heave, Pitch and Roll effect	2,190,698	Null	Null

As seen in Table 4, volume calculations using Hypack showed that heave affect the total estimated volume by only 0.011 % while pitch and roll affect the total volume calculation by only 0.0004 % so the correction resulted out from ship motion can be neglected.

Based on these results, it is clear that heave, pitch and roll did not have significant effect on volume calculations, because of calm sea states in the most of Suez Canal which did not affect single beam survey.

Furthermore, Tin models were created by applying the four cases in the first test area. Then, the depth profile was plotted for the different correction cases as shown in Figure 9. This figure represents a sample of sea bed profile; however, the rest of the data shows the same behavior.

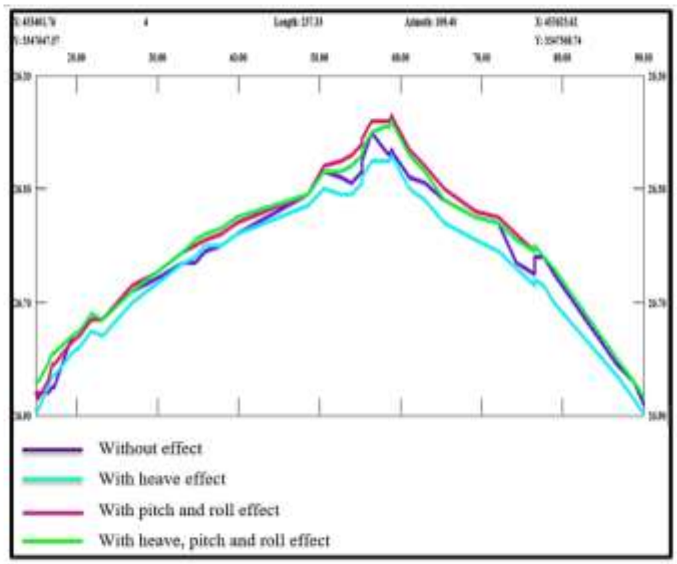

Figure 9: Sea Bed Profile Considering Vessel Motion Sensors in First Test Area

Figure 9 shows that the line indicates the case (with pitch and roll effect) is nearer to the case (with heave, pitch and roll effect) and this proves that pitch and roll has negligible effect on survey data.

Finally, to further assess the effect of motion correction on volume calculations accuracy, the root mean square value for the errors of each parameter was calculated to evaluate the errors induces by motion sensors on depths readings. The equations below represent how the root mean square error was calculated.

- $\delta_{\text{heave corr.}} = D_{\text{measured depth}} - D_{\text{corrected depth by heave}}$
- $\delta_{\text{pitch and roll correction}} = D_{\text{raw depth}} - D_{\text{corrected depth by pitch and roll only}}$

The following equation represents the Root Mean Square Factor for either (heave) or (pitch & roll) cases:

$$\text{RMS} = \sqrt{\frac{\delta_1^2 + \delta_2^2 + \delta_3^2 + \cdots + \delta_N^2}{N-1}}$$

Where:

RMS Root Mean Square

δ Correction of either heave or (pitch and roll)

N Number of Events (selected data)

The following figure shows the root mean square value of heave, pitch and roll correction for the first test area in new Suez Canal project.

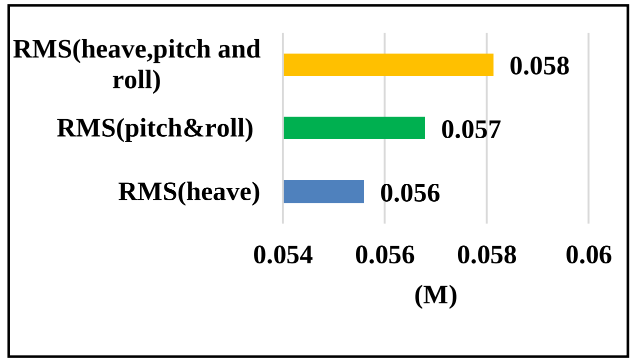

Figure 8: Root Mean Square Values in Different Cases of Motion Sensors Effect

As shown in Figure 10, RMS values calculations agree with the previous findings.

2. Third Test Area (New Suez Canal)

In the third test area, the currents are relatively higher than other parts in the Suez Canal. Figure 11 shows the heave values in the third test area.

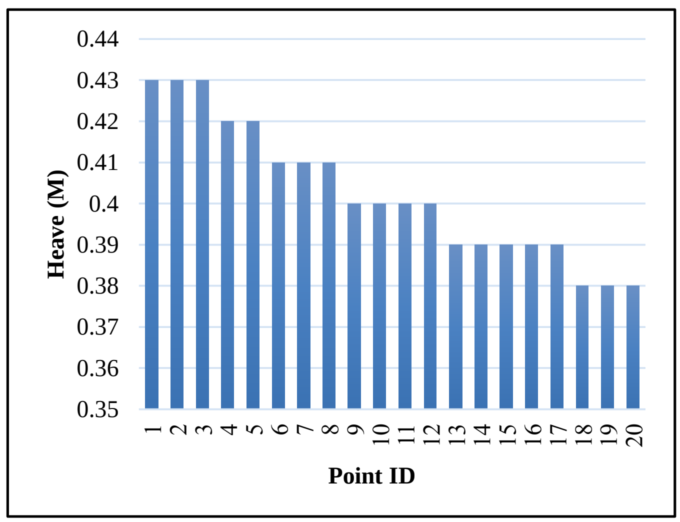

Figure 9: Data sample clarifying Heave Effect on Depths Readings in third Test Area

Heave values clarified in Figure 11 indicates that it can affect the measured depths in contrary of the other two test areas, the total number of points in this investigation in the third test area were 15585.

TABLE 52
THE STANDARD DEVIATION OF HEAVE CORRECTION IN THIRD TEST AREA

Min (m)	Max (m)	Mean (m)	Stand. deviation
-0.15	0.45	-0.0024	0.013282

The conf. level for heave correction for the whole data in the third test area equal
Conf. level = 1.96*STND
=1.96*0.013282=0.026 m

The confidence level of heave correction in the third test area is beyond the allowable vertical uncertainty. The following figure show the pitch and roll values of the third test area.

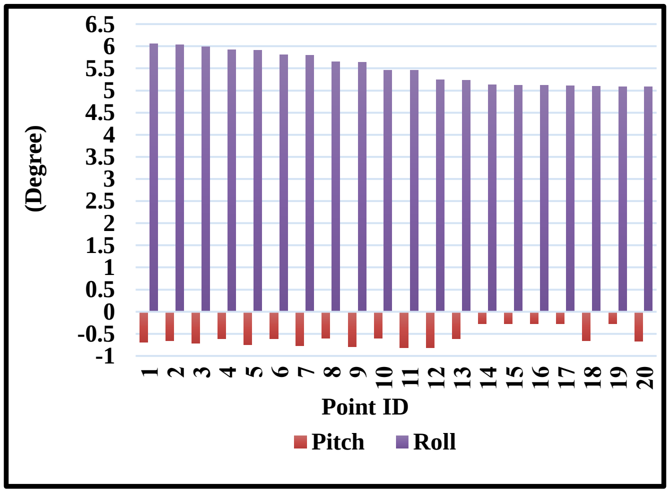

Figure 10: Pitch and Roll Values in the Third Test Area

Figure 12 shows that due to high currents in third test area there is high pitch and roll values reach up to 6 degrees which can affect measured depths.

TABLE 6
THE STANDARD DEVIATION OF PITCH AND ROLL DIFFERENCE IN THIRD TEST AREA

Pitch (deg.)		Roll(deg.)		Mean (m)	Stand. Dev.
min	max	min	max		
-1.4	2	-4.3	6.05	-0.00025	0.0133

The conf. level for pitch and roll correction in the third test area equal
Conf. level = 1.96*STND =1.96*0.013287=0.027 m
The confidence level of pitch and roll correction in the third test area is beyond the allowable vertical uncertainty.

Figure 13 shows pitch and roll affect the measured depths so it can affect volume calculation.

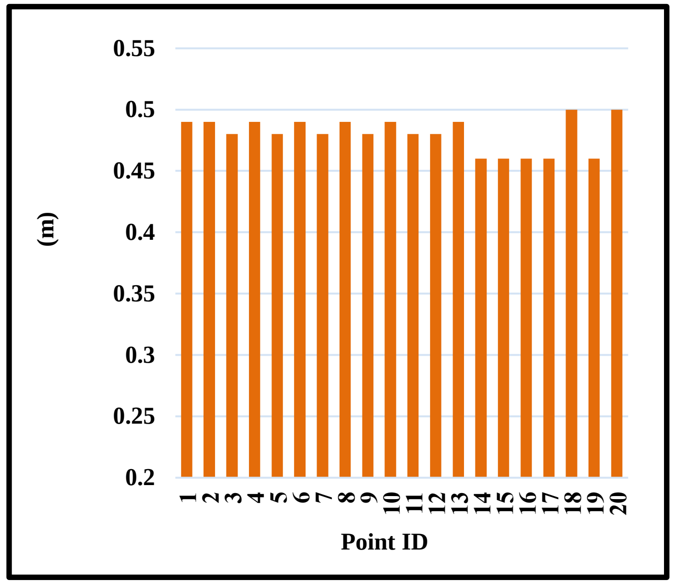

Figure 11: the difference between the measured depths and the corrected depths induced by Pitch and Roll

TABLE 7
DIFFERENCES IN VOLUME QUANTITY DUE TO MOTION SENSORS EFFECT

Cases	Volume Quantity (m^3)	Diff. (m^3)	Percent. (%)
Without any effect	918,341	1,644	0.18
With Heave effect	919,497	488	0.05
With Pitch and Roll effect	919,165	820	0.1
With Heave, Pitch and Roll effect	919,985	Null	Null

Table 7 represents the volume calculations in different cases using Hypack. It can be seen that heave affect volume calculation by 0.1 % while pitch and roll affect by 0.05 % and both of them affect volume by 0.18% so these results cannot be neglected comparing to other results. This shows that heave, roll and pitch induce effect on depths readings.

This could be explained by the high-sea states and currents in the third test area and this is clear in the following figure.

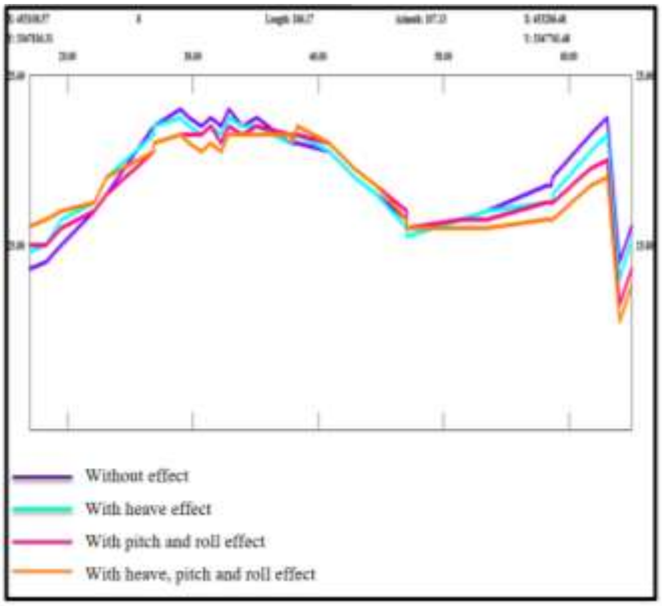

Figure 12: Sea Bed Profile Considering Vessel Motion Sensors in Third Test Area

From Figure 14 It is clear that all ship motion parameters have significant effect on dredged volume calculation and thus on project cost.

The root means square values were calculated as before, Figure 15 shows the RMS values that validates the previous analysis.

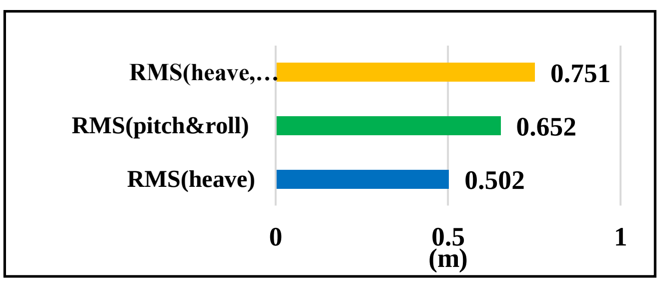

Figure 13: Root Mean Square Difference

It is concluded that, all motion parameters shall be included in rough sea conditions for their substantial effect.

B. The Effect of Different Software on Calculating Volume Quantities

The volume calculation was tested by using three different 3D software packages, which were HYPACK, CIVIL 3D and ARC GIS, and the results are compared in the following chart.

Software Package	Suez Canal Project								
	Area 1			Area 2			Area 3		
	Dredging Volume	Diff.	%	Dredging Volume	Diff.	%	Dredging Volume	Diff.	%
Hypack	825,011			1,890,162			1,265,425		
		277	0.03%		9,442	0.50%		11,434	0.90%
Civil 3D	824,734			1,880,720			1,253,991		
		40,974	4.97%		94,517	5.00%		54,368	4.30%
ArcGIS	783,760			1,786,203			1,199,623		

Figure 14: Difference in Volume Computations Using Different Software

The comparison in Figure 16 showed almost consistent results between the Hypack and the Civil 3D packages for the three data sets of the Suez Canal project where the tolerance is in the range of about 1% while the Arc GIS showed tolerance in the range of 4 to 5 % compared to the other 2 software packages. In the Boubian test area, the Arc GIS showed consistent results with the Civil 3D package while its tolerance with the Hypack is relatively higher in the range of 7.5%.

VII. Conclusion

A. Ship Motion Effect:

(I) Great Bitter Lakes of the Suez Canal Test Area

The bathymetric survey data obtained from this project was divided into three data sets. In the first and second data sets, the maximum effect of heave on the measured depths was 30 cm and the maximum 95% confidence level is 4 cm which is in the allowable value of total vertical uncertainty for the investigation, while the maximum effect of pitch and roll was 13 cm. In the first data set, heave affects the dredged volume by 0.011 % while pitch and roll affect by 0.0004%. In the second data set heave affects the dredged volume by 0.02% while pitch and roll affect by 0.0007%.

In the third data set the maximum effect of heave was 45 cm and the maximum effect introduced by pitch and roll was 50 cm while the 95% confidence level for both heave and pitch and roll corrections was 2 cm. Heave affects the dredged volume by 0.1% while pitch and roll affect by 0.05 %.

B. The Effect of Using Different Software in Calculating Dredged Volume

Three software packages were used to calculate the dredging quantities in single beam bathymetric survey using data collected from two different projects. These packages are; Hypack, Civil 3D and ARC GIS. Only Hypack was used in hydrographic data post processing and the other two were used to create TIN model and *then calculate the dredging volume.*

Recommendations

- It is recommended to carry out further research to assess the vessel motion parameters when using multi beam sonar particularly in open sea areas. Furthermore, comparison between Lidar bathymetric survey and multi beam sonar survey will be very useful. Such comparison must focus on the accuracy of calculated dredging volume and also on time and cost of survey.

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