Table of Contents

LABORATORY MEASUREMENT OF FORCES ON A DREDGE CUTTER HEAD

D. R. Young[1] and R. E. Randall[2]

ABSTRACT

Dredge cutting forces produced by the movement through the sediment have been measured with the laboratory dredge carriage located at the Haynes Coastal Engineering Laboratory. The sediment bed that was used for the dredging test was considered to be relatively smooth and the sediment used was sand with a d_{50}=0.27 mm. Forces on the dredge carriage were measured using five 13.3 kN (3000 lb) one directional load cells placed on the dredge ladder in various places so the transmitted cutting forces could be obtained. The objectives for this study were to determine the vertical, horizontal, and axial forces that are produced by the cutterhead while testing. So, to find these cutter forces, a static analysis was done on the carriage by applying static loads to the cutterhead in the vertical, horizontal, and axial directions, and for each load that was applied, readings were taken for all five of the load cells. Then, static equilibrium equations were developed for the dredge carriage ladder to determine loads in the five load cells. Also, equilibrium equations can be applied to a dredging test to find the cutterhead forces by taking the measured data from the five load cells and applying the known forces to the equations and from this the cutterhead forces can be determined. These static equilibrium equations have been confirmed by using a program called SolidWorks, which is modeling software that can be used to do static finite element analysis of structural systems to determine stresses, displacement, and pin and bolt forces. Data that were gathered from the experimental procedure and the theoretical calculations shows that the force on the dredge cutterhead can be determined.

Keywords: cutting forces, dredging angle, cutter RPM, swing speed, and static loading.

INTRODUCTION

Forces induced on the cutterhead are very important because these forces are transmitted from the cutterhead through the ladder and up to the ladder supports. Also, the cutting forces are significant when trying to design the swing winches and deciding what type of swing anchors to use. From this, it shows that forces on the cutterhead are important and these forces have demonstrated great interest for many researchers. This research topic has been researched by a number of researchers including S. A. Miedema (1987) and (1989), A.G. van Os and W. van Leussen (1987), and W. J.Vlasblom (2005).

For the current research that was performed at the Haynes Coastal Engineering Laboratory, takes into account an entirely new concept on how the forces on the cutterhead are determined. This concept entails using the dredge carriage in the dredge/tow tank facility shown in Figure 1. The dredge carriage is a 1:6 model of a 0.6096 meter (24 inch) cutter suction prototype dredge. The dredge carriage has a maximum digging depth of approximately 0.67 m (2 ft). Figure 1 shows the ladder cradle, upper and lower ladder, articulating arm, and cutterhead. For the current research of cutting forces on the cutterhead, a full scale computer generated model was drawn using a program called SolidWorks, which is a three dimensional modeling software that has the capabilities of modeling true scale structures (weight and dimensions). In Figure 1 (right), a finished full scale model of the prototype dredge carriage is shown and is compared with the prototype carriage. The full dimensions of the carriage are as follows, length =5.102 m (200.85 in), width =4.045 m (159.25 in), and the height of the lower and upper ladder = 5.958 m (234.56 in). The cutterhead that is used is a 0.343 m (13.5 in) diameter with a five blade system with a pitch of approximately 29 degrees. The carriage is oriented in a system of north, south, east, and west directions, and this system is used to describe locations of instruments on the dredge carriage. In the current cutting force research this system was used to describe the locations of the load cells.

[1] Graduate Research Assistant, Center for Dredging Studies, Ocean Engineering Program, Zachry Department of Civil Engineering, Texas A&M University, College Station, Texas, Tel: 979-777-5873, Fax: 979-862-8162, Email: dyoung@neo.tamu.edu.
[2] Director, Center for Dredging Studies, Ocean Engineering Program, Zachry Department of Civil Engineering, Texas A&M University, College Station, Texas, Tel: 979-845-4568, Fax: 979-862-8162, Email: r-randall@tamu.edu.

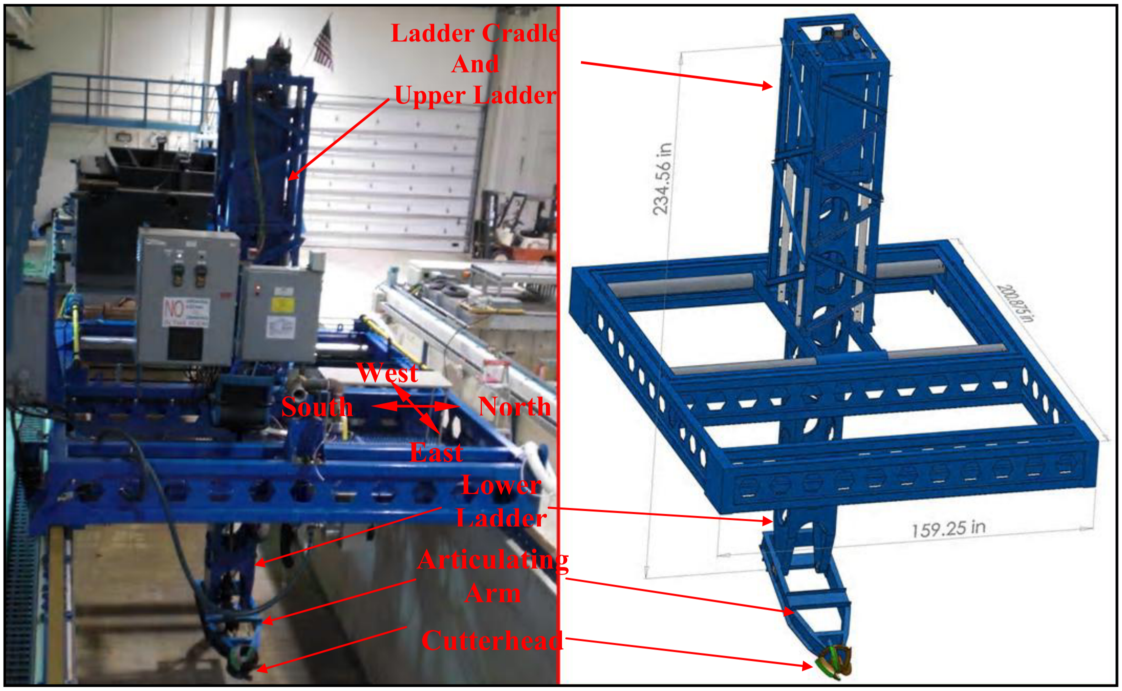

Figure 1. Prototype dredge carriage (left), SolidWorks model dredge carriage (right)

To measure forces on the dredge carriage ladder, the concept of using one dimensional load cells in varies locations to get an accurate reading of the transmitted forces from the cutterhead. The load cells were placed in locations that would keep the ladder as rigid as possible, so that the force readings are accurate. The load cells that were used are a one dimensional 13.3 kN (3000 lbf), which was considered to have plenty of load capacity while doing a dredging test. These load cells are Omega Engineering LC202-13.3 kN (3000lbf) gauges and have an accuracy of $\pm$ 0.25% which in this case is approximately 0.033kN (7.5 lbf) and the load cells have a ultimate over load of 300%, safe over load of 150%, and the output signal is 2 mV/V (Omega 2008). For the final design of the carriage, five of the 13.3 kN load cells were used and placed in the locations shown in Figure 2. Load cell 1 was positioned were it would take most of the vertical load or weight of the ladder and is shown in Figure 2 to be positioned in the center of the ladder and located at the very top. Cells #2 and #4 were positions to the north and south directions and in this position the north to south forces of the cutterhead will be resisted. Finally cells 3 and 5 are positioned to the east to west direction and are located so that they pick load from the torsional effect of the ladder and also pickup load when an east or west forces are applied to the cutterhead.

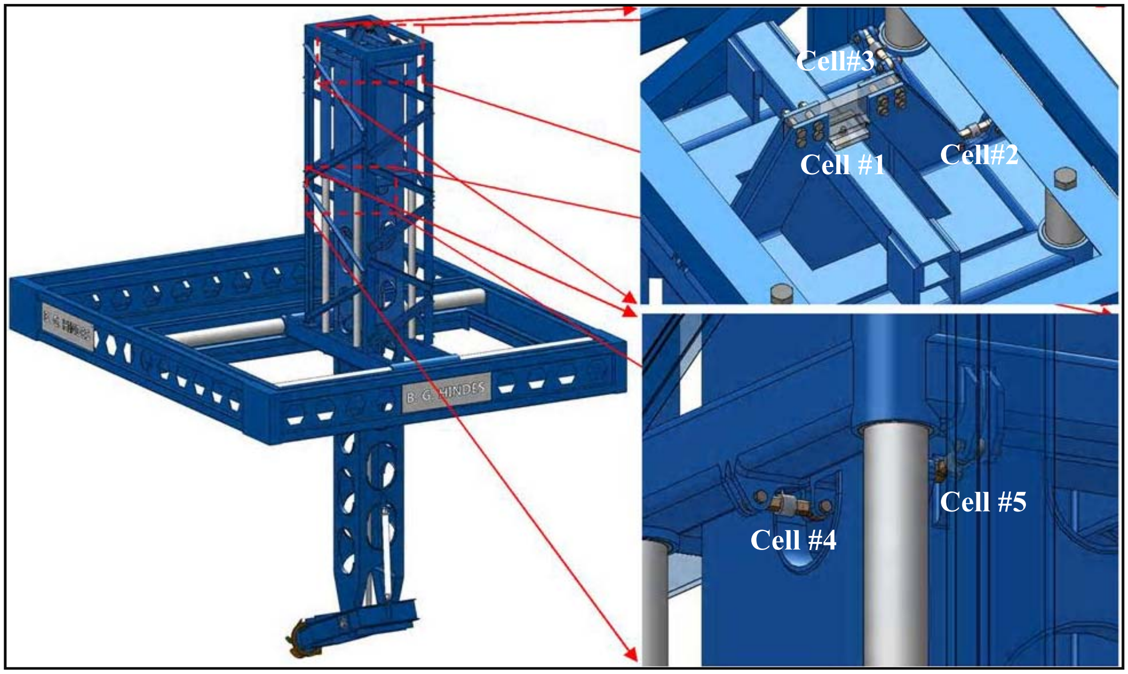

Figure 2. Description of load cell locations

Calibration Procedure of Load Cells

For the current research a number of instruments had to be calibrated to achieve good results. To calibrate the five load cells on the carriage a procedure was developed for calibrating the calibrator cell and the five carriage load cells.

Calibration of Calibrator Cell

For the calibration of the five load cells another source of knowing the load on the carriage cells had to be known. This was done by using another load cell and this was an Omega Engineering LC202- 17.79kN (4000 lbf) one directional cell and this cell has the same specifications as the LC-202- 13.3 kN. This cell is powered and the output (mV) recorded with a strain gauge indicator.

The calibration of the cell was accomplished using a 22.24 kN (5000 lb) load cell. A 35.585 kN (8000 lbf) come-along was used to apply the load to the load cell. In Figure 3 (left), it shows how the load cell, come-along, and lab scale were attached together by 26.69 kN (3 ton) shackles and (3 ton) chain. In the figure it is shown that the configuration is attached to the floor by a floor anchor and the lab crane was used to secure the top of the configuration. The load cell had to be calibrated in the tension and compression state and was done as follows. In Figure 3 (middle) the tension test is shown and consist of just applying load in tension direction in approximately 0.889 kN (200 lbf) increments until the maximum was reached of +17.79kN (4000lbf). Now the final compression calibration was done and can be seen in Figure 3 (right). This test was a little more difficult because a compression device had to manufactured, which is the blue device in Figure 3.

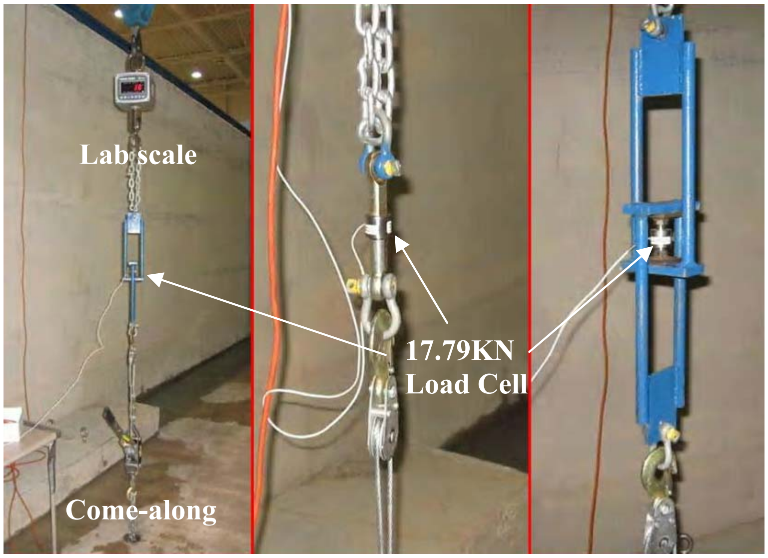

Figure 3. Calibration procedure for the calibrator cell

After the calibration was completed the data had to be processed to get the calibration equation that was needed. The program MATLAB was used to produce Figure 4 and to get the best fit line that is needed to get the calibration equation. In Figure 4, it is shown that the collected data were sufficient and is confirmed by a R^2 value of one. In Equation 1 the mV (millivolts) is the output of the strain gauge indicator and the Load is the load that the cell is experiencing. So the calibrator cell is calibrated and the next process was performed.

$$\boldsymbol{Load}(\boldsymbol{lbf}) = 172.9605 \times (\boldsymbol{mV}) - 6.3004 \quad (1)$$

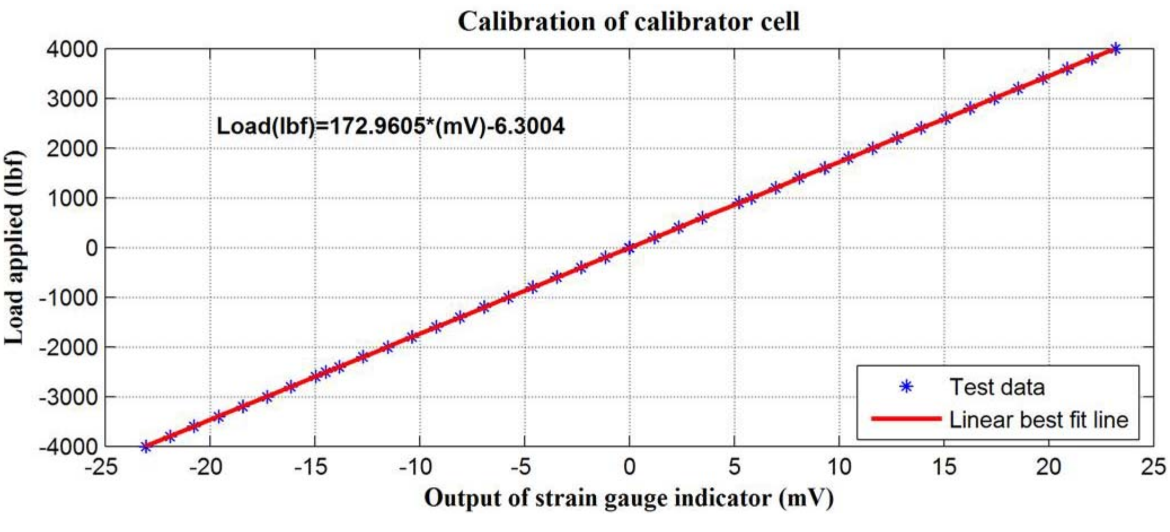

Figure 4. Calibration of calibrator cell

Calibration of Dredge Carriage Load Cells

Now that the calibrator cell is calibrated; the five load cells on the dredge carriage can be calibrated. The same type of procedure needs to be preformed for the carriage cells. The problem that was encountered was that the load cells on the carriage couldn't be taken off because they were hard wired. Also the data acquisition system that is used for the carriage takes data as a percent (%) not in millivolts like the calibrator cell does. Since this was the case, a procedure had to be developed so that the carriage load cells could be calibrated on the carriage. So a calibration bracket shown in Figure 5 was designed with the assumption that the two load cells, if put in line together, would read the same force. The simple concept of using a hydraulic jack was used to apply the force to get a tension and compression load by putting the jack in the lower quadrant to get a tension load and repeat the process by moving the jack to the upper quadrant to get a compression load on the cells. After the concept was confirmed, the bracket was drawn using 3.81 cm x 3.81 cm (1.5 in x 1.5 in) 11 gauge A 992 steel square tubing for the structure and tested in a program called SolidWorks to check the design, and the outcome was that a maximum deflection of 0.7747 cm (0.305 in) occurred at the end of the tension and compression arm when a 4.89 kN (1100 lbf) force was applied. So the design check showed that the current design would be sufficient for the calibration procedure.

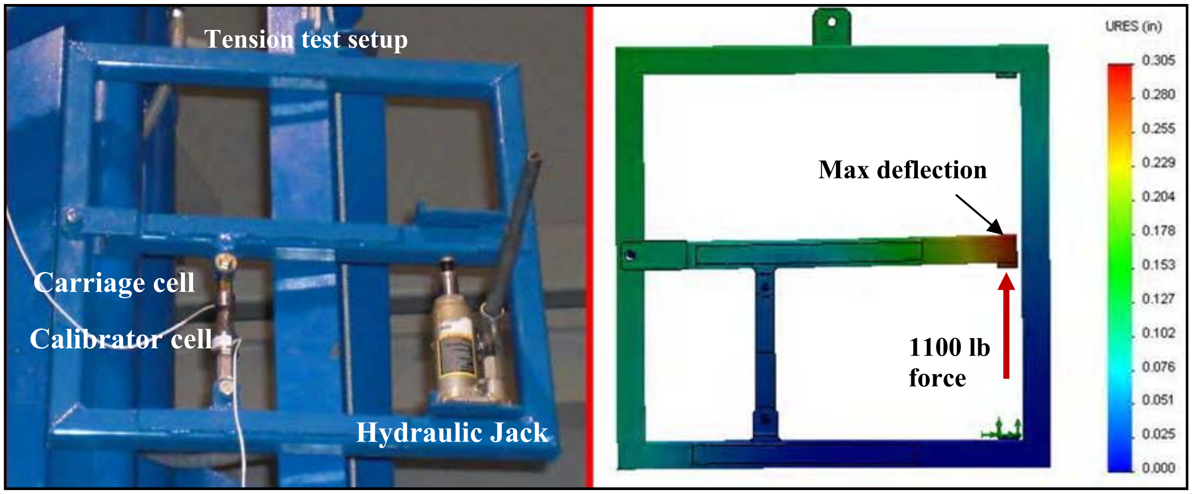

Figure 5. Carriage load cell calibrator bracket (left) and SolidWorks Displacement of cal bracket (right)

The calibration procedure for calibrating the dredge carriage load cells was finish and then the calibration was started. The test consisted of applying load in approximately 0.889 kN (200 lbf) increments up to the maximum of the 13.3 kN (3000 lb) load cell. This procedure was repeated for both the tension and compression situations for each of the five cells. After the data was obtained, MATLAB was used to plot the data for all of the load cells. The plotted test data are shown in Figure 6 and was generated using the percent (%) value from the data acquisition system of the dredge carriage and the y-axis is the converted output from the calibrator load cell. A linear best fit line was used to determine the calibration equation that is used to convert the test data that is obtained for the test procedure.

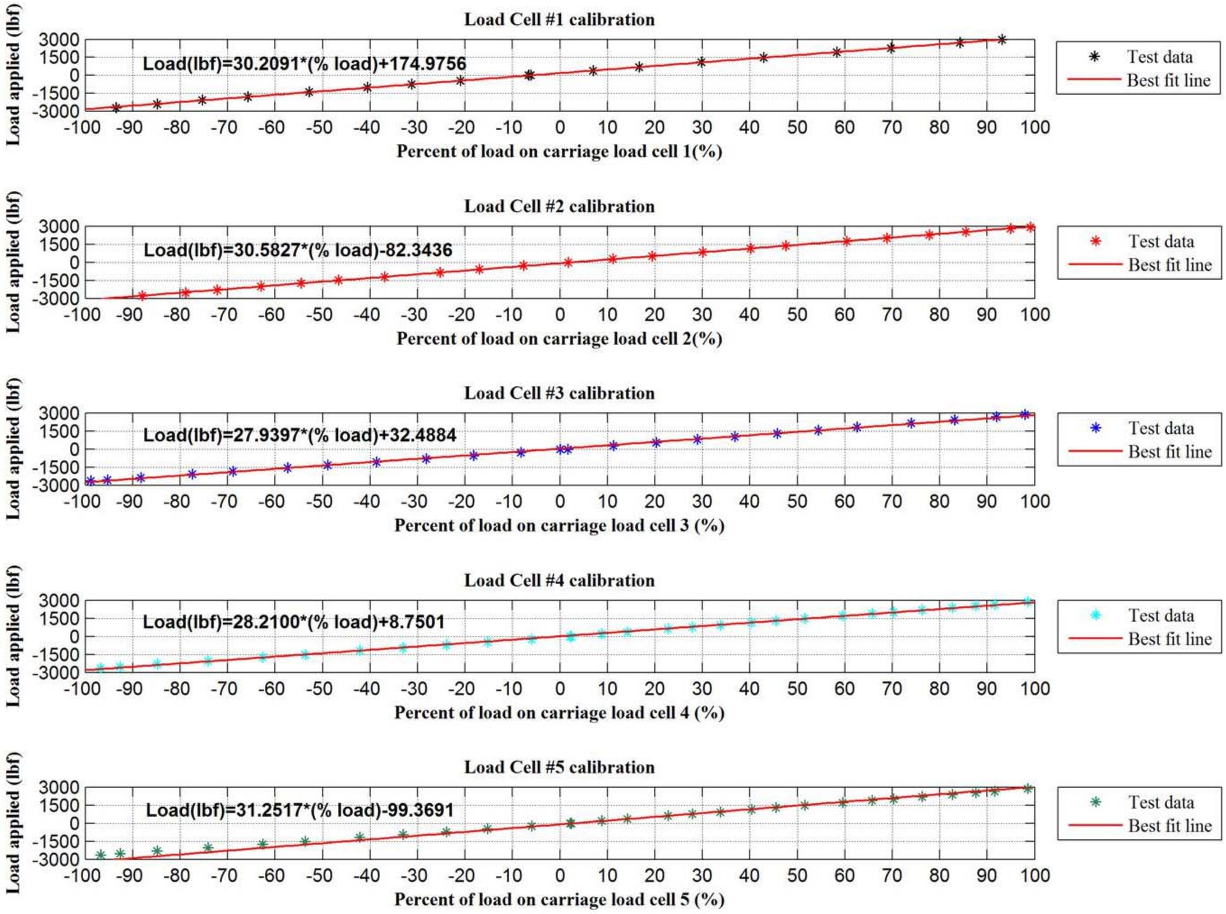

Figure 6. Calibration plots for all five load cells

In Figure 6 the calibration equations are shown for the five load cells, and these are the equations that are used to convert the raw data from the data acquisition system. The raw data of the dredge carriage data acquisition system is in percent load, and that's why the only input variable for the five load cell equations are percent load. The only gauge that was skewed a little was cell 5 on the compression side, but this can be corrected by recalibrating the compression side, however in this case the error is less than 5%, so the recalibration was not done.

Testing Procedures for Determining Forces in the Loads Cells

For the testing to be done, in determining the forces on the dredge carriage cutterhead can be approached in three different methods. The first method is the actual laboratory tests that were done at the Haynes Coastal Engineering Laboratory. The second test consists of using a program called SolidWorks to determine loads in the five load cells. The last applied test is the theoretical approach which assumes static loading on the dredge carriage ladder, and from this assumes the static equilibrium equation can be written for carriage ladder. From these three tests, conclusions are made on how well the research approach in determining cutting forces on the dredge cutterhead. The three tests are accomplished by applying a known load to the cutterhead to achieve results for the five load cells.

Lab Testing Procedure

The laboratory procedure was done to acquire data for the experimental results that are required to see how close the theoretical results compare, and this determines if the force reading in the five loads are adequate. The laboratory procedure consists of using the calibrator cell to read load that was applied at the cutterhead. In the top left-hand corner of Figure 7 the pulling procedure is shown and this pulling procedure was completed for pulls in the south to north, north to south, east to west, and west to east directions, and in the figure the pulls are demonstrated. To apply the load, a 17.79 kN (4000 lbf) come-along was use, and was restrained by fixing one end to a tow tank floor anchor and the other end to the cutterhead. To get an accurate measurement of the apply force on the cutterhead; the pulling device had to be carefully place where it was parallel to the floor and perpendicular to the cutterhead. In doing this, the other procedures can have improved repeatability and accuracy.

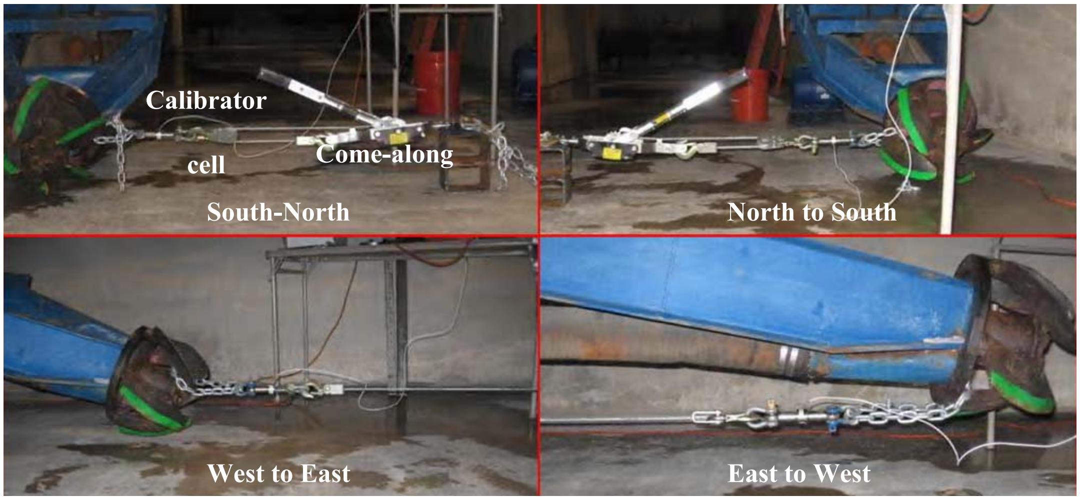

Figure 7. North, south, east, and west pull directions

The load on the cutterhead was applied in increments of approximately 0.45 kN (100 lbf) up to 1.779 kN (400 lbf) of load and was completed for each of the pull directions. For each of the pull increments approximately 5 seconds of data was taken by the dredge carriage data acquisition system and this data will be converted form percent load to pounds using the equations from the calibration process of the five load cells. For each of the pulls the articulating arm had to be set with a specific angle or also known as dredging angle (θº). On a prototype dredge the dredging angle corresponds to the digging depth which the ladder is set for. For the dredge carriage, the articulating arm is set for a specified dredging angle shown in Figure 8, and the digging depth is adjusted by an up and down drive motor on the ladder. The test procedure was done for a dredging angle of 0º, 11º, and 22º, this was done to compare how the forces in the five load cells correspond to different dredging angles. From this testing procedure conclusions will be drawn if the current cell configuration is adequate.

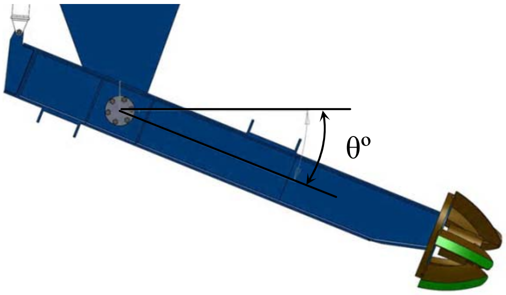

Figure 8. Dredging angle (θº) description

SolidWorks Program Procedure

For the SolidWorks procedure a model of the dredge carriage had to be drawn to scale to achieve good results from the program. The SolidWorks program is a three dimensional modeling software that has the ability of developing full scale models with same dimensions and material property as the prototype structure. The SolidWorks program has a toolbox called Cosmosworks and is capable of doing a finite element analysis of a structure to achieve displacements, stress and strains, and loads in pins and bolted connections. The mesh for the finite element analysis that was used had a global size of 3.05cm (1.2in) and has a tolerance of 0.15cm (0.06in). The setup that was used is shown in Figure 9 which only considers the ladder and the articulating arm in the analysis because the other dredge carriage structure are not needed to get the desired load in the load cells. The SolidWorks program settings that were used are the linear static analysis tool. This analysis tool is considered to apply load in small iterations to get a true static analysis of the structure, and this is done to account for the deformation movement of the structure.

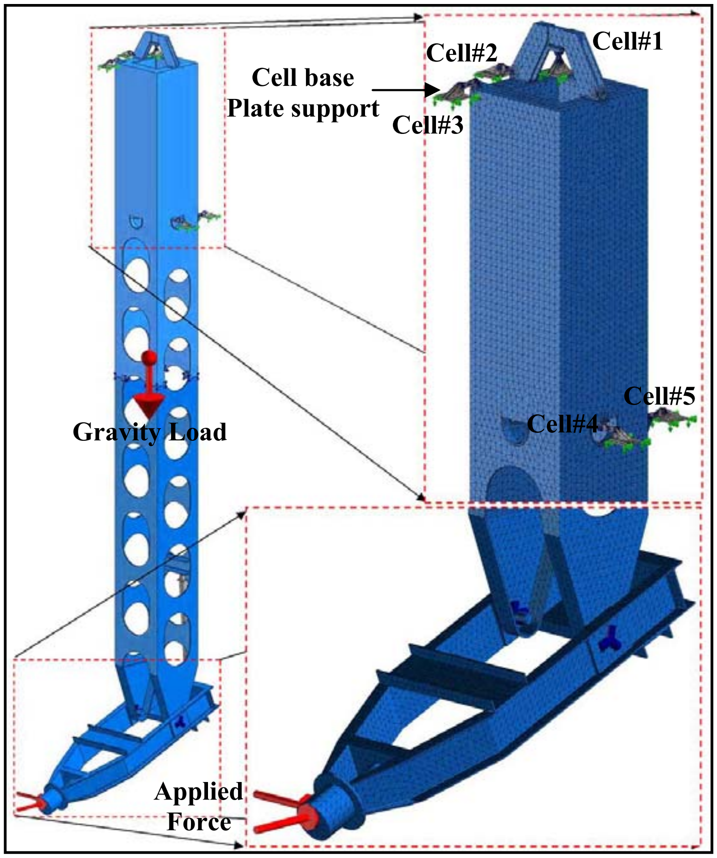

Figure 9. SolidWorks finite element model

The setup of the program consisted of applying pins where two parts are joined together, and for each through hole, two pins had to be used. To fully define the model, fifty two pins were used, and to get the load in each cell, the load cell locations were replaced with a pin connects so the result of the axial load in the pin is consider the force which the load cell would be experiencing. In Figure 9, the cell base plate is shown and this technique was used to replace the ladder cradle which takes the place of the restraints of the load cells. The five base plates shown in the figure are restrained in all six degrees of freedom. The gravity load of the structure was applied to the center of gravity to take the weight of the structure into account. The same procedure was done for this test as it was done for the laboratory testing procedure, and this was done by applying load at the cutterhead location shown in Figure 9. The same directions of pulls and loads were used in this procedure as the laboratory test.

Ladder Force Equilibrium Equation Procedure

The third and final test done was the theoretical analysis of the ladder structure to determine the forces in the five load cells by using static force equilibrium approach. For the equation development of the force equilibrium equations for the dredge carriage ladder, the Riley and Struges (1996) static structures textbook was reviewed, and from the review Equation 2 is used to determine these equilibrium equations. In Equation 2, it is assumed to have no dynamic affect to the structure only static loading.

$$\begin{array}{lll} \sum \boldsymbol{F_x} = \boldsymbol{0} & \sum \boldsymbol{F_y} = \boldsymbol{0} & \sum \boldsymbol{F_z} = \boldsymbol{0} \\ \sum \boldsymbol{M_x} = \boldsymbol{0} & \sum \boldsymbol{M_y} = \boldsymbol{0} & \sum \boldsymbol{M_z} = \boldsymbol{0} \end{array} \quad (2)$$

For Equation 2 a main coordinate system was considered to be located at the cell#1 location at the top of the ladder. For the equation development, the sign convention used is shown in the top right corner of Figure 10. From the SolidWorks analysis, a large shear force was found at the cell 1 location. From this analysis, an assumption was made that the shear force at this location was in the plus or minus direction along the x axis and this direction depends on the pull direction of the applied load to the cutterhead. So from this assumption the force was assumed to be in the positive x direction and is shown in Figure 10 as F_{c1x}. In Figure 10, the weight of the ladder and the articulating arm are described as W_{lad} and W_{aa}. The weight and the location of the center of gravities used for the W_{lad} and W_{aa} values were produced from the SolidWorks model of the dredge carriage.

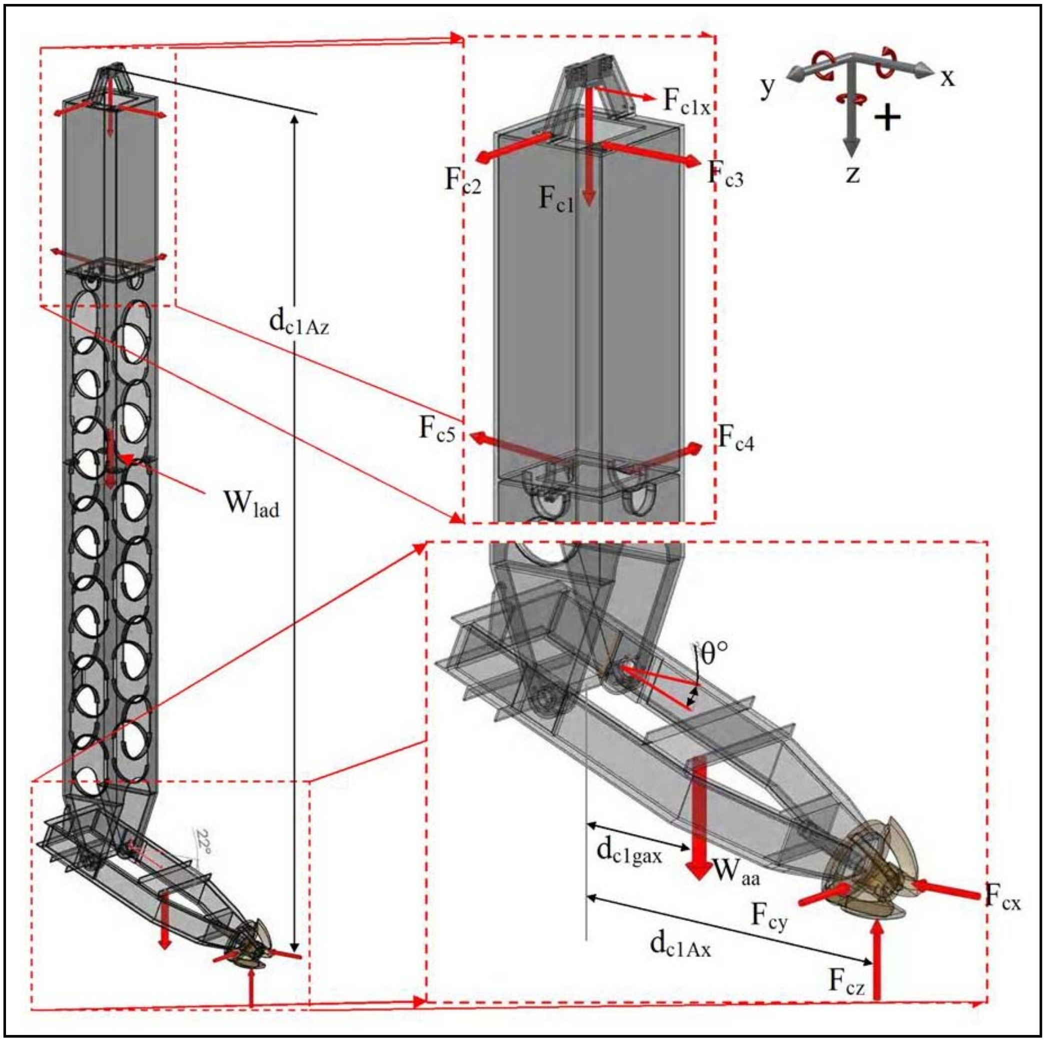

Figure 10. Free body diagram of dredge carriage ladder

The five forces in the load cells are described by F_{c1}, F_{c2}, F_{c3}, F_{c4}, and F_{c5}, and the subscript c# represents the cell number that it represents. In the summation of the equations the F_{c4} and F_{c5} values had to be split up in x and z components because the two cells weren't exactly perpendicular to the ladder. So the values for these values were $F_{c4x}=F_{c4}\sin 89.9$, $F_{c4z}= F_{c4}\cos 89.9$, $F_{c5x} = F_{c5}\sin 84.9$, and $F_{c5z}= F_{c5}\cos 84.9$ and these were used for the equation formation. The axial, horizontal, and vertical cutting forces are describe by the values F_{cx}, F_{cy}, and F_{cz} , and the location of the cutting forces were considered to be applied at the center of mass of the cutterhead shown in Figure 10. All of the forces have been described and now the summation of force in the x, y, and z directions can be tabulated. The summation of moments for the ladder was taken at the location cell#1 and from this position the distance to the center of mass of the articulating arm and distances to the cutterhead had to be determined. The distance from cell1 to the center of mass of the articulating arm along the x-axis is shown in Equation 3 and this distance has the variable theta (θ) which represents the dredging angle that was described in the laboratory procedure test. The distance from cell#1 to the cutting force location are given by Equations 4 and 5, and these distances also are a function theta.

$$d_{c1gax} = 21.2992 * cos(\theta - .5237) \tag{3}$$

$$d_{c1Ax} = 55.0212 * \cos(\theta - .4556) \tag{4}$$

$$d_{c1Az} = 234.56 + 55.021 * \sin(\theta - .4556) \tag{5}$$

Now that the distances for the center of mass for the articulating arm and cutting force location have been defined, the summation of moments can be taken about the x, y, and z axis. From the summation of forces and moments in the x, y, and z directions, six equations were formed and can now be used to determine forces in the five load cells. Equation 6 is the final form for the six equilibrium equations and from Equation 6 it can be seen that there are nine unknowns.

$$\begin{bmatrix} 0 & 1 & 0 & 0 & -.00175 & -.0888 & 0 & 0 & -1 & 1 & 1 \\ 1 & 0 & 0 & 1 & 0 & -.996 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & -.9999 & 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -9.25 & 0 & -9.0885 & 0 & -d_{c1Ax} & 0 & 0 & 0 \\ 0 & 0 & -5.25 & 0 & 59.5107 & 0.8111 & 0 & d_{c1Az} & 0 & 0 & 0 \\ 0 & 0 & 0 & 5.25 & 0 & -60.7556 & -d_{c1Az} & 0 & d_{c1Ax} & 0 & -d_{c1gax} \end{bmatrix} \times \begin{bmatrix} F_{c1s} \\ F_{c1} \\ F_{c2} \\ F_{c3} \\ F_{c4} \\ F_{c5} \\ F_{cx} \\ F_{cy} \\ F_{cz} \\ W_{lad} \\ W_{al} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{6}$$

To achieve results similar to the laboratory and SolidWorks procedure, Equation 6 had to be rearranged. Now to get results for the two other testing procedures the values F_{cx}, F_{cy}, and F_{cz} had to be considered as known variables. In assuming this, Equation 6 was rearranged to get Equation 7 which has six unknowns and six equations, so in this form the system of equations can be solved. A program generated with Matlab was used to solve the system of equations for the same loads that were applied to the cutterhead location in the other two procedures.

$$\begin{bmatrix} 0 & 1 & 0 & 0 & -.0018 & -.0888 \\ 1 & 0 & 0 & 1 & 0 & -.9960 \\ 0 & 0 & 1 & 0 & -.9999 & 0 \\ 0 & 0 & 0 & -9.25 & 0 & -9.0885 \\ 0 & 0 & -5.25 & 0 & 175.0241 & .8111 \\ 0 & 0 & 0 & 5.25 & 0 & -60.7556 \end{bmatrix} \times \begin{bmatrix} F_{c1x} \\ F_{c1} \\ F_{c2} \\ F_{c3} \\ F_{c4} \\ F_{c5} \end{bmatrix} = \begin{bmatrix} -W_{lad} - W_{aa} + F_{cz} \\ F_{cx} \\ F_{cy} \\ F_{cy}d_{c1Ax} \\ -F_{cy}d_{c1Az} \\ F_{cx}d_{c1Az} + W_{aa}d_{c1gax} \end{bmatrix} \tag{7}$$

Results from all Testing Procedures

The results from the testing procedures or carefully inspected and from this inspection a conclusion will be drawn. The data results for the laboratory, SolidWorks, and the equations procedures were all gathered and the Matlab program used to generate the graphs for all of the tests results. The data from all of the five loads cells and tests are used to generate the graphs for each pull direction. From the graphs conclusions will be made if the load cells are responding the way they are expected to.

The north pull results for all of the procedures will be reviewed first. So in Figure 11 the output from Matlab is shown and the legend gives the description of each line. When looking at the configuration of each load cell on the ladder it can be seen visually that cell 2 and cell 4 should take most of the load when a force in the south to north direction is applied, and cells 3 and 5 should be picking up the torsional effect of the twisting of the ladder. In Figure 11 cells 2 and 4 are taking an applied load, but cell 3 is shown to be taking most of the load and cell 5 to be taking no load at all. This load on cell 3 is to be expected, but cell 5 is being affected by the interference of cell 1 in the shear direction, which this shear effect is resisting load and that load is considered to be applied to cell 5. In Figure 11 it can be seen that the results from the SolidWorks and equations procedure have little error and can be considered to be very close. The cell 1 results shows that the SolidWorks and equation procedures are close, but the laboratory results show a different load rating and this could be due to the ladder shifting and redistributing the load in a different cell, however results from the procedure for cell 1 has a similar slopes as the other two. Now looking at cells 3, 4, and 5 which show a good result when the three procedures are compared, however the only big difference is the offset of the procedure results with the other two. As described for cell 1 this is due to the load that are in the cells when no load is applied to the cutterhead. A shift occurs in cells 3 and 4 at 1.668kN (375lbf), which could be caused with interference from the ladder cradle. The cell that has a good difference from the other two test is cell 2, which shows a great difference in slopes from the procedure results to the other two and could be because of interference of the ladder cradle again, but the other pulls will be reviewed to make sure cell 2 is taking readings properly.

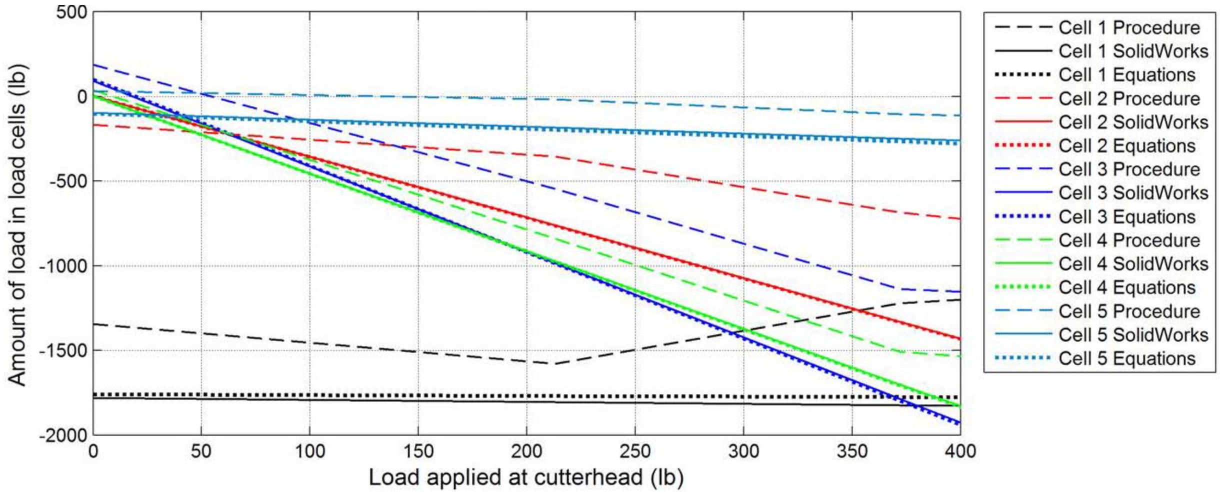

Figure 11. North pull for all testing procedures

The south pull results are reviewed and conclusions drawn on the accuracy of the cells when considering cutting forces in the north to south direction. The results from the laboratory, SolidWorks, and equations procedures for the south pull have been graphed to show how accurate the cells are for each procedure. In Figure 12 results for cell 1 can be seen that they are resemble the north pull results to start with, however the slopes are different and in the south pull results of cell 1 shows that the laboratory results better resembles the SolidWorks and equation results. For cell 1 the laboratory results are offset from the other two because of variables in the laboratory, however this can be corrected when the cutting forces are calculated. The results for cell 1 are reasonable and show that good results can be approximated. Again by visual inspection cells 2 and 4 should be resisting the load of the south pull and cells 3 and 5 should be resisting the torsional affect for the twisting of the ladder. From the results cell 4 readings are close, but cell 2 again are off considerably from the SolidWorks and equations results. In this pull test there is an irregularity at 0.889kN (200lbf) and above of applied load which could be again be caused by ladder cradle interference while doing the laboratory procedure test. This test pull shows good results for cells 1, 3, 4, and 5, but cell 2 shows to have more error in this pull direction than in the north pull procedure.

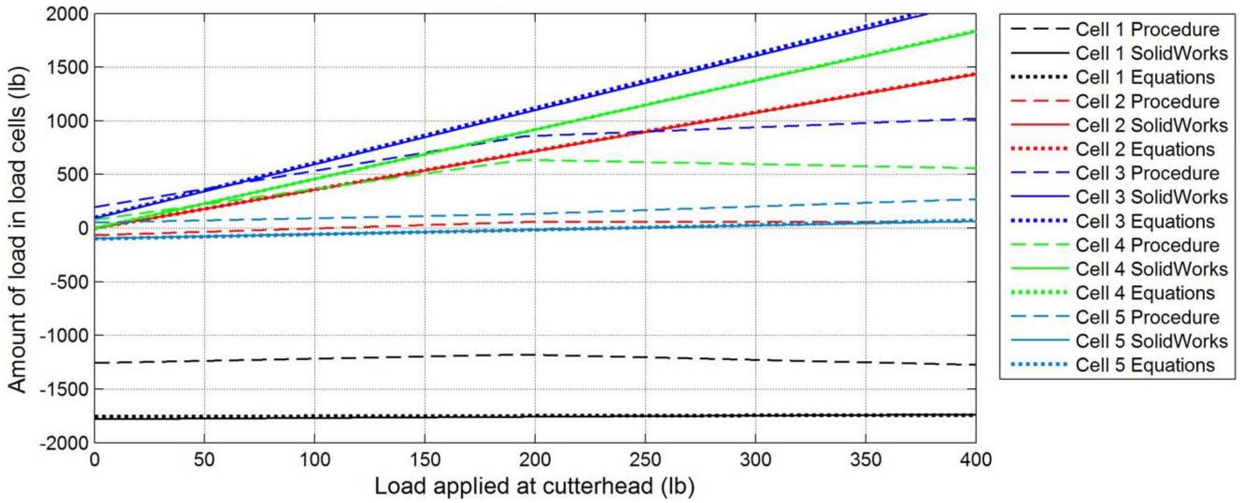

Figure 12. South pull for all testing procedures

The East pull results are now reviewed and conclusions drawn on the accuracy of the cells when considering cutting forces in the west to east direction. In Figure 13, cell 1 is shown to react the same as the other two pulls and it is shown to be consistent with the SolidWorks and equations procedures. By visual inspection of the cells when a west to east pull is done, it can be expected that cells 3 and 5 take most of the load. In Figure 13 this loading of cell 3 and 5 are to be expected and this shows that the two cells are working properly when a west to east load is applied to the cutterhead. In Figure 13, the SolidWorks and equations results can’t be seen but this is due to the results from cell 4 covering them and this is expected because when a west to east pull is applied these two cells should be reading approximately the same. The laboratory results for cell 2 to be offset a small amount and this could be due to a ladder shift. The same shift in the reading occur the same applied load and again this will be considered in the cutting forces calculation. For this pull tests, the results look to be accurate and show that good results can be expected when calculating cutting forces.

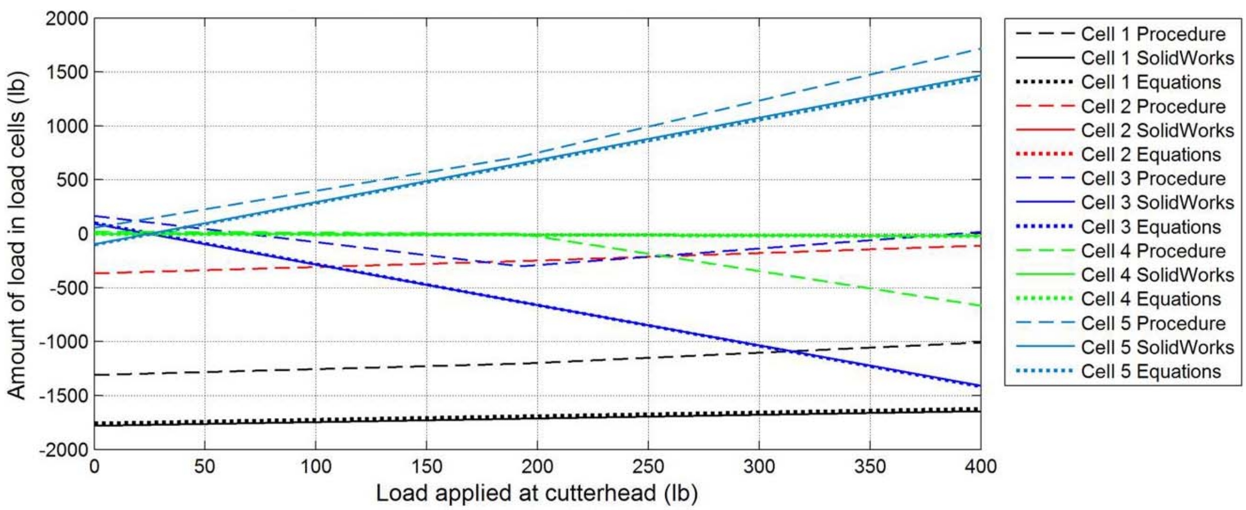

Figure 13. East pull for all testing procedures

Finally, the west pull results will now be reviewed and conclusions drawn on the accuracy of the cells when considering cutting forces in the east to west direction. In Figure 14 cell 1 is shown to reacting slightly different than the other test, but this is due to different starting value than the other test and could be due again to ladder shift. In Figure 14 cell 3 and 5 have the same results has the east pull, but are oriented different do to the different pull direction. This test has the same similarity as the east pull and even have the same shift at the same loading as the other pull test. Again the results look appropriate and show that good results can be expected for the cutting force calculations, however again the data for cell 2 will be inspected carefully.

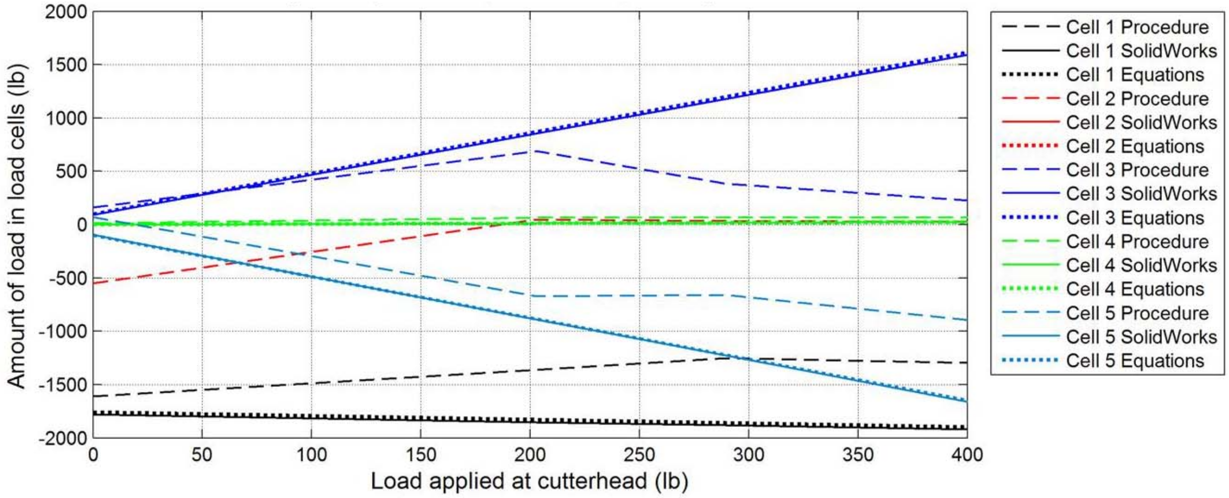

Figure 14. West Pull for all testing procedures

From the following results of the laboratory, SolidWorks, and equations procedures have shown good results on the cells working properly for the load cell configuration. The results however show irregularities in the five loads when a force of approximately 0.8896 kN (200 lbf) and above are applied to the cutterhead in the north, south, east, and west pull directions. Also, the results from cell 2 show that readings are sometimes skewed and inaccurate for the north and south directions, but in the east and west directions the gauge seems to be working properly. This irregularity will be taken into consideration when the cutting forces are being calculated. The results from the three procedures have produced favorable results and shows that the cutting forces on the cutterhead can be approximated accurately.

Cutting Force Results for Dredging Test

The main results from all of this research testing of the dredge carriage are the actual results for the cutting forces on the cutterhead while doing a dredging test. For the results for the cutting forces F_{cx}, F_{cy}, and F_{cz} to even be possible, some assumptions had to be made. These assumptions consist of the forces in the loads cells correspond equally with the forces that are generated with the force equilibrium equations. So with this assumption, the forces that are recorded from the data acquisition system for a dredge test can be converted using the calibration equations for the five load cells, and then these outputs are directly inputted into the force equilibrium equations to achieve the cutting forces at the center of mass at the cutterhead. From the equilibrium equations generated by the equation method the assumption that the loads in the five loads cells are known and the cutting forces and shear force in cell 1 are unknown. So Equation 6 was rearranged to get this configuration for F_{c1}, F_{c2}, F_{c3}, F_{c4}, and F_{c5} as known values and F_{c1s}, F_{cx}, F_{cy}, and F_{cz} as unknown values and this form of the system of equations is shown in Equation 8.

$$\begin{bmatrix} 0 & 0 & 0 & -1 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & -d_{c1Ax} & 0 \\ 0 & 0 & d_{c1Az} & 0 \\ 0 & -d_{c1Az} & 0 & d_{c1Ax} \end{bmatrix} \times \begin{bmatrix} F_{c1s} \\ F_{cx} \\ F_{cy} \\ F_{cz} \end{bmatrix} = \begin{bmatrix} F_{c1} + F_{c4}(.00175) - W_{lad} - W_{aa} \\ -F_{c3} + F_{c5}(.996) \\ -F_{c2} + F_{c4}(.9999) \\ F_{c3}(9.25) + F_{c5}(-9.0885) \\ F_{c2}(5.25) - F_{c4}(59.5107) - F_{c5}(.8111) \\ -F_{c3}(5.25) + F_{c5}(60.7556) + W_{aa}d_{c1gax} \end{bmatrix} \tag{8}$$

So by using Equation 8 the unknowns F_{c1s}, F_{cx}, F_{cy}, and F_{cz} can be solved for each iteration, which for the data acquisition system dredge carriage the gauge readings are taken at 1 Hz or 1 reading per second. A dredging test for the dredge carriage is approximately between 100 sec and 400 sec depending on the criteria of the specific dredge test. So to get results for each iteration of a test, a program had to be developed to solve the system of equation for each iteration. The MATLAB program was used to develop the wanted program, which consist of the input of the acquired data from the test and a loop was formed to solve the systems of equation for each iteration, and from that it was stored in a matrix were graphs of the results could be generated. So now by using this program, results of the cutting forces induced on the dredge cutterhead can be generated for a specific dredging test.

In the summer of 2008 two dredging test were completed using the dredge carriage. The parameters that need to be defined for these tests are the flowrate (LPM or GPM), swing speed velocity (cm/sec or in/sec), cutter advancement (cm or in), cutter RPM, and depth of cut (cm or in). The depth of cut is set visually by a scale on the side of the ladder and the flowrate and cutter RPM are set by inputting a percent value for each into the dredge carriage operating system. The parameters that are automated for these two specific tests are the swing speed velocity, cutter advancement, number of cuts, and distance travel for each cut. This automation was done by John Henriksen and was input into the operating system of the dredge carriage so the test could be done. These two tests that were used for the research on forces induced on the cutterhead were done by John Henriksen, Arun Manikantan, and Dustin Young. These tests were for Arun Manikantan's production research; however when the tests were in progress the data were taken for the five load cells on the carriage and used in the cutting forces research.

The first dredging test observed is test#1 which consists of a cutter RPM of 86, flowrate of 1135.5 LPM (300 GPM), and depth of cut of 20.32 cm (8 in). The cutter advancement and swing speed velocity were calculated by using data from Figure 15 which shows the swing position and cutter advancement position. From the data, an average cutter advancement was calculated to be approximately 36.83 cm (14.5 in) and swing speed velocity was calculated to be approximately 2.29 cm/s (0.905 in/s).

The output of the program for the cutting forces of test 1 are shown in Figure 15, which shows the values for F_{cx} (Axial Cutting Force), F_{cy} (Horizontal Cutting Force), and F_{cz} (Vertical Cutting Force). The dredging test consists of three cuts and this is shown by how many cutter advancements are taken. The cutting forces correspond to the directions of loads on the cutterhead shown in Figure 10 which F_{cx}, F_{cy}, and F_{cz} are all shown to be in the negative direction relative to the coordinate system in Figure 10. In Figure 15 the same cutting force directions are used, and if the cutting forces are negative, that means that the assumed forces are in the opposite direction than they are in Figure 10.

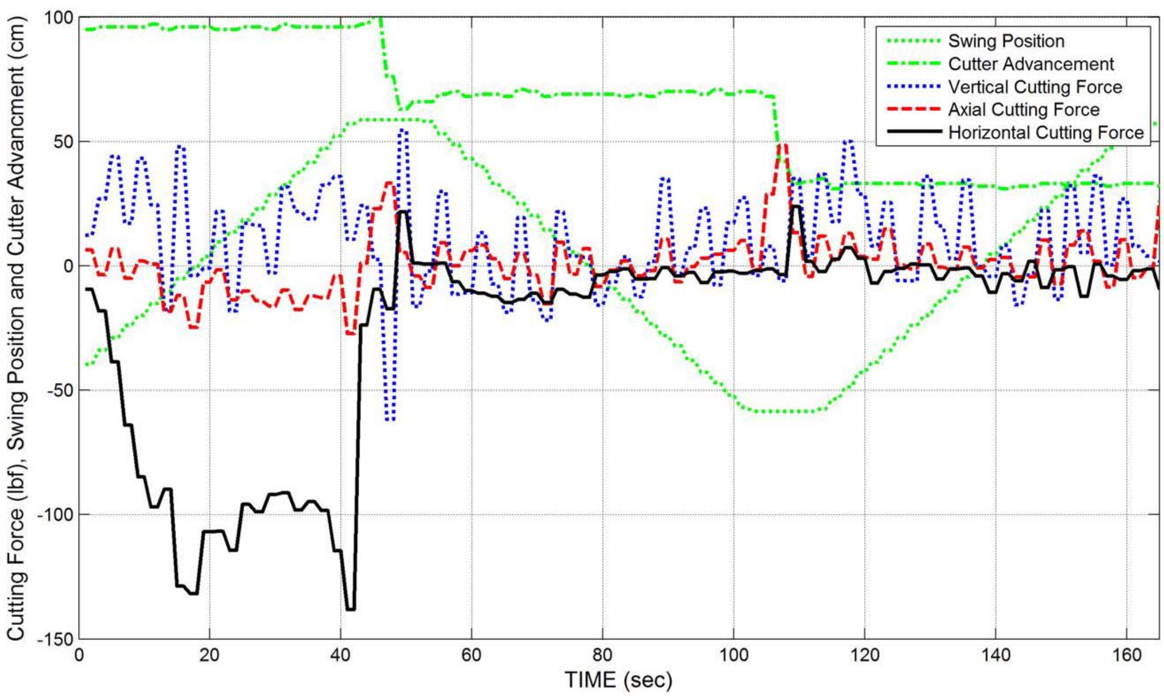

Figure 15. Calculated cutting forces for summer 2008 test#1

In Figure 15, the swing position is shown to have a positive or negative slope which depends on the direction of swing. This direction of swing is very important because this determines if overcutting or undercutting is occurring.

For the dredge carriage the cutterhead rotates counterclockwise when viewed from the front and this defines overcutting when the cutterhead moves from a north to south direction, and undercutting is defined by the cutterhead moving in the south to north direction and this can be observed in Figure 16. So in Figure 15 when the swing positions slope is negative overcutting is occurring, and when the slope is positive undercutting is occurring. The overcutting and undercutting will significantly have an effect on the forces induced on the dredge cutterhead. So now that the cutting force directions and the description of overcutting and undercutting for the dredge carriage have been defined, some observations can be made about the graphed cutting force data in Figure 15.

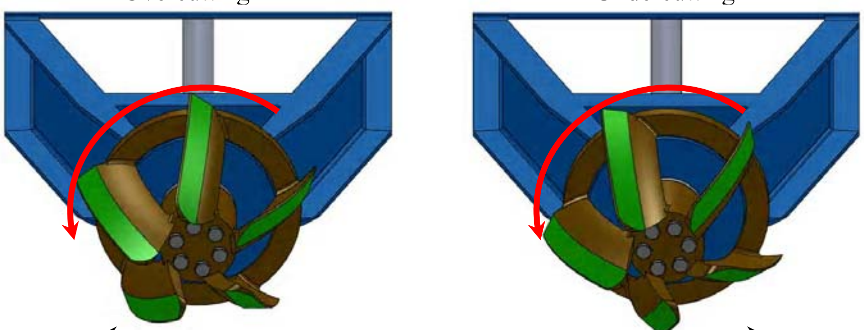

Figure 16: Demonstration of overcutting (left), and undercutting (right)

The first thing that needs to be considered is to determine if the shift that was determined by the procedure results occurs in the dredging test 1. To determine if the shift occurs Figure 15 is used to determine if a 0.889 kN (200 lbf) and above force are experienced in the test. Looking at Figure 15, it can be seen that a 0.889 kN force is not experienced in the test, so the cutting forces can be assumed to be accurately calculated. For the calculation of the cutting forces, the cell 1 load was modified to fit the equation procedure better and by doing this the results for F_{cx} and F_{cz} were shifted to the zero line and in doing this the forces weren't affected. The modification was done by taking the mean cell 1 from the test data, and this mean was subtracted from the total weight (W_{lad}+ W_{aa}) that was used for the equation formation, and then the output was added to the mean weight to get a value that is more closely related to the weight used to form the equations. In Figure 15, it can be seen that a large horizontal cutting force was experienced, and this is due to the buildup of sand on the articulating arm which caused the elevated cutting force, but when the cutter advances the cutting force diminishes and this situation isn't experienced again for the rest of the cuts. This is because the articulating arm is free of the weight of the sand because the articulating ladder is in the first cutting path which the sand has already been removed. This buildup of sand on the articulating arm was visually observed for the dredging test and the force on the ladder confirms the experience of the sand buildup. In Figure 15, it can be seen that when the cutterhead advances between cuts, a jump in the axial load is experienced. This jump is to be expected because the cutterhead is getting pushed through the sediment, and the forcing of the sand is reacting on the cutterhead which leads to this jump in the axial load on the cutterhead. In Figure 15, cut 2 is shown to have gradual upward slope and for cut 3 a gradual downward slope of the cutting forces are shown, and this is due slight sand buildup and due to overcutting for cut 2 and undercutting for cut 3. So the cutting forces for test 1 have shown accurate results and have shown that cutting forces can be determined using this method of research.

The second dredging test consists of all the same parameters as dredging test 1 and this helps in confirming that the cutting forces obtained from test 1 are sufficient. For this test the same automation program was used and no changes were made, so the swing position and cutter advancement position are the same as test 1 and can be confirmed by Figure 17. In Figure 17, the results for the cutting forces for test 2 are shown and can now be compared to the results from test 1. In Figure 17, cut 1 shows that the same thing happens when the first cut is done and this due to the same thing in test 1 which is sand buildup on the articulating arm. So cut 1 shows that the similar thing happened in test 1 and this confirms when the first cut is in progress a large horizontal cutting force is experienced. Also, in Figure 17 it can be seen when the carriage advance between cuts a large axial force is experienced and this same phenomenon was experienced in test1. The last thing that was observed for test 1 was undercutting and overcutting issue and for test2 it can be seen that for cut2 there is slightly upward slope of the cutting forces and for cut3 a downward slope is observed for the cutting forces. So this show that the cutting forces can be calculated accurately for two repeated dredging test. From test 2 confirmations can be made that the cutting forces for this research procedure approximately accurate. To show how little difference there are between test 1 and test 2 a graph was generated by Matlab and this shows the results in the same figure.

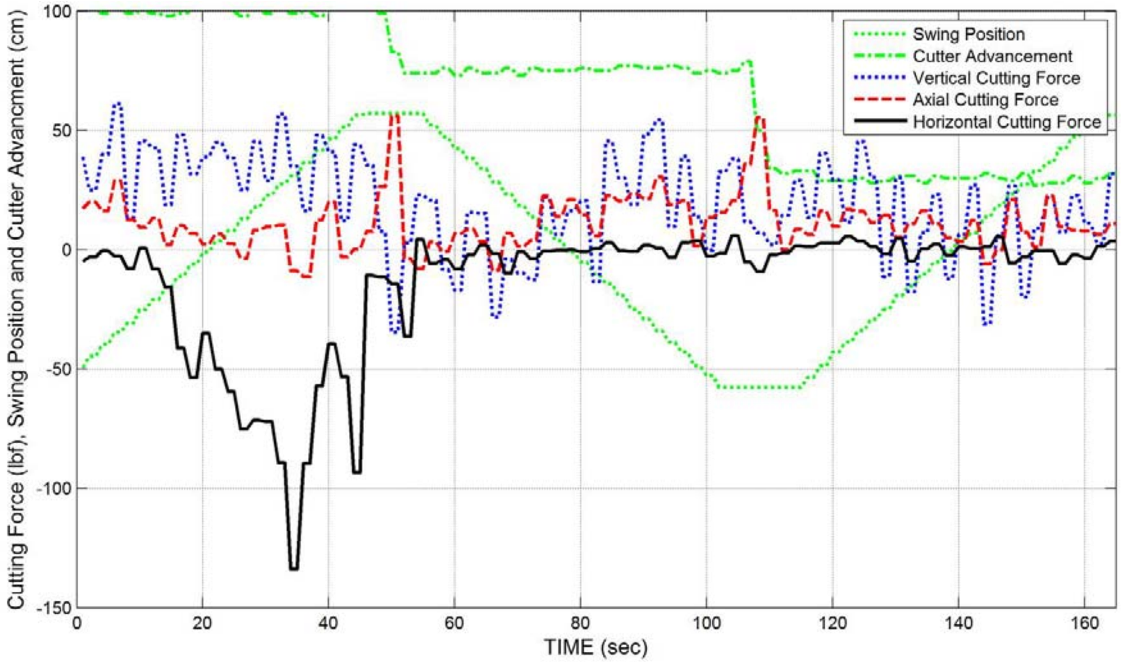

Figure 17. Calculated cutting forces for summer 2008 test#2

To show how the tests compare, a graph was generated with Matlab. In Figure 18 the overlay graph of the two dredging test are shown and from this graph the similarities of the two test can be seen.

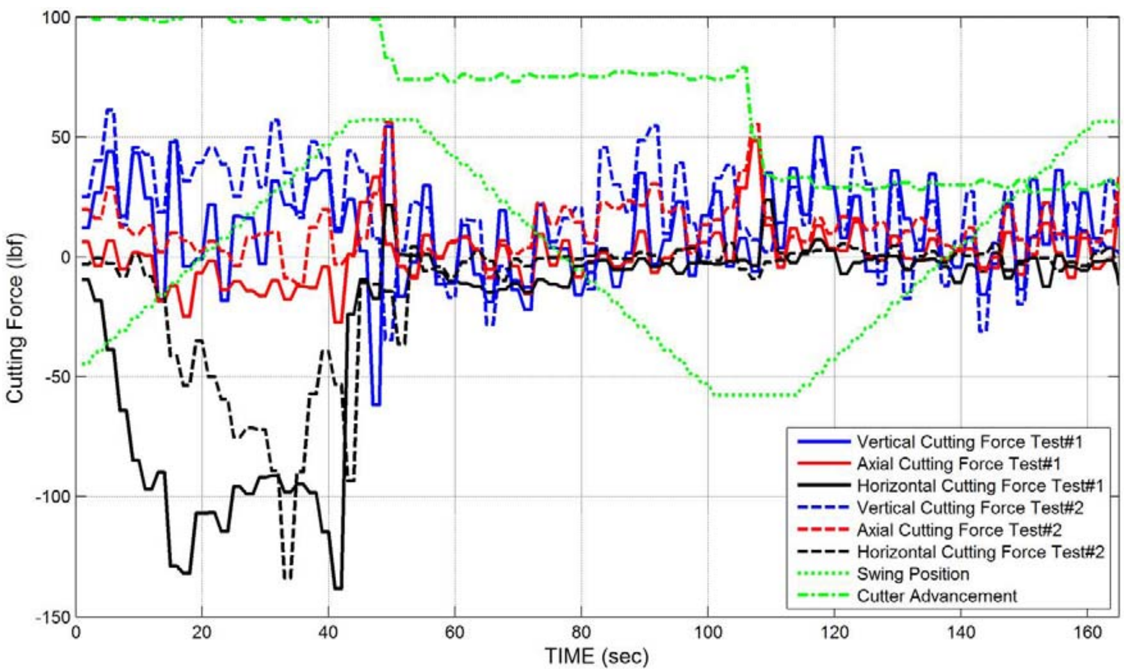

Figure 18. Test #1 and #2 overlaid

From this results section, the equations from the equation procedure have been rearranged so the cutting forces for a dredging test could be calculated and from this the systems of equations in Equation 8 were developed. Thus, the raw data from the carriage have been converted by using the calibration equations developed for the five load cells and the output from these equations were input into the program developed using MATLAB and the cutting forces were calculated and graphed for the two dredging tests done in the summer of 2008. Consequently, graphical observations were made and it was determined that the calculated cutting forces were correct.

CONCLUSIONS

The research approach in determining forces induced on a model cutter suction dredge cutterhead has been completed and now the results can be evaluated. To achieve good results the calibration of the calibrator cell and the five loads cells on the carriage completed and the results from the tests shows that the calibration equations for the six load cells are accurate and can be used to process the data for the carriage data acquisition system . The results for the laboratory testing procedure have been processed, and the results are accurate. The results from the SolidWorks procedure have been processed and these results show that the laboratory and SolidWorks results correspond to one another. The static equilibrium procedure has been completed and the static equilibrium equations have been developed for the five load cells. These equations can be rearranged to get results for the type of procedure done for the laboratory and SolidWorks procedure, or can be rearranged to get cutting forces at the cutterhead if the loads in the five load cells are known. So the calibrations and the research procedures have been completed and they show that close results can be generated for the forces induced on the cutterhead.

ACKNOWLEDGEMENTS

The forces induced on a model cutterhead research was performed at the Haynes Laboratory and the dredge carriage design was funded by the Barrett G. Hindes Foundation and without this facility and funding this research wouldn't been able to be completed. The conceptual design of the dredge carriage was completed by Glover (2002) and Glover and Randall (2004), and from this the final design of the carriage was completed by Digital Automation and Control Systems, Inc. (DACS) and Oilfield Electric Marine (OEM), a subsidiary of Rowan Companies. The completed dredge carriage was installed in the laboratory in April 2005. Thanks to the development of this facility and the development of the dredge carriage this research was possible.

REFERENCES

Glover, G.J. (2002). "Laboratory Modeling of Hydraulic Dredges and Design of Dredge Carriage for Laboratory," Master of Science Thesis, Ocean Engineering Program, Civil Engineering Department, Texas A&M University, College Station, TX.

Glover, G. J. and Randall, R. E. (2004). "Scaling of Model Hydraulic Dredges with Application to Design of a Dredge Modeling Facility," Journal *of Dredging Engineering*, WEDA, Vol. 6, No. 2, September.

Miedema, S.A. (1987). "The Calculation of the Cutting Forces when Cutting Water Saturated Sand, Basic for 3-Dimensional Blade Movements with Periodically Varying Velocities for in Dredging Usual Excavating Elements." Doctoral dissertation, Technical University of Delft, The Netherlands.

Miedema, S.A., (1989). "On the Cutting Forces in Saturated Sand of a Seagoing Cutter Suction Dredge". Proc. WODCONXII, Orlando, Florida, USA, April.

Omega Engineering, Inc 1. "LC202 Miniature Universal Load Cells." (2008). March 3, 2009 <http://www.omega.com/Pressure/pdf/LC202.pdf>

Os, A.G. van and Leussen, W. van. (1987). "Basic Research on Cutting Forces in Saturated Sand". Journal of Geotechnical Engineering, Vol. 113, No.12, December.

Riley, W. F. and Sturges, L. D. (1996). "Engineering Mechanics Statics." Second Edition. John Wiley & Sons: Canada.

SolidWorks 2008-2009 for Windows. (2009). Santa Monica, CA :Dassault Systèmes.

Vlasblom, W. J., "Cutter Suction Dredge" May 2005 <http://www.dredging.org/documents/ceda/downloads/vlasblom3-the-cutter-suction-dredger.pdf>