FLOODSTAND-deliverable:

DESIGN GUIDELINES FOR PLACEMENT AND TECHNICAL REQUIREMENTS OF FLOODING SENSORS IN PASSENGER SHIPS

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Abstract:
Detection and measurement of flooding onboard a damaged ship are presented. Different sensor types are briefly reviewed and the requirements for sensors in respect of flooding prediction are discussed. Finally some general technical requirements and guidelines for placement of the sensors are presented.

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CONTENTS

1 EXECUTIVE SUMMARY

Decision making in a damage situation requires that the outcome of the damage can be predicted. Evaluating and predicting the stability of a damaged ship requires that the flooding extent is known. There are several ways of actually calculating the stability during flooding, and some methods like NAPA flooding simulation tool use the size and location of the breach. Breach can be estimated if the flooding is measured accurately enough. Simpler methods require only that the flooding extent is known.

The first step in a damage situation is that flooding is detected. This text takes a step forward from this and analyses the requirements of flooding sensors when they are used for a Decision Support System. The more accurately the flooding extent and amounts are measured the better the predicted results are. Accurate measurements of flooding enable more tools for evaluating the stability of the ship and the consequences of flooding.

Generally the more accurate the flooding measurement system is, the more expensive it becomes and shipyards and owners are reluctant to install equipment that is not useful to their ships. However in practice reliable Flooding Detection systems and more fine tuned Decision Support systems have very similar sensor requirements. Both design types share high expectations about the sensor reliability and testing possibilities. Current requirements for Flooding Detection are not considered adequate.

Current state-of-the-art flood-water detection sensors are reviewed and the use of measurement data for flooding prediction is discussed. The main emphasis is on the level sensors since they provide the possibility to evaluate also the flooding rates and use of inverse method, which are essential for estimation of the breach size and location.

A case study on the number of flooding sensors in a large passenger ship was performed. The results indicate that with a moderate sensor density of 0.26 (26% of modeled rooms were equipped with a sensor) breach could be detected in most cases but not all. It is recognized that there is currently some ambiguity in what typical flooding sensor systems are capable and how reliable they are.

Finally, on how to design a reliable and comprehensive flooding detection system, some guidelines for sensor placement and requirement are presented as well as some typical compartment layouts with sensor placement examples.

2 BACKGROUND

The target of Task 3.3 is to derive principles/guidelines for design of flood sensors systems in passenger ships, e.g. to define the required number, type (level sensor or on/off switch) and location of the flooding sensors, testability, specification of technical requirements for flooding sensors concerning accuracy, operability, interfaces, installation, etc.

Ultimate goal is to have a Decision Support system that allows the captain to be able to base his decision in emergency situations on reliable and accurate information. Current installations based on only flooding detection do not meet this criterion.

Level sensors are an important part of Flooding Detection and Decision Support systems (*Nilsson and Rutgersson, 2006 and Ruponen, et al., 2011*), and following the guidelines presented in this text it is possible to design a decision support system that allows:

- Ship's crew to get a fast detection of flooding before stability of the ship is compromised.
- Crew to monitor water amounts all over the ship (excluding spaces which do not have real significance).
- Use of onboard and shore systems, which can calculate the residual stability and give instructions to the crew based on the real flooding extent.
- Real-time analysis using inverse method to determine breach size and location from measurement.
- Predictions of progressive flooding in actual conditions and comparison to actual flooding

The stability of a damaged ship can be calculated with static methods or by simulating flooding extent in time-domain with dedicated simulation methods, such as NAPA Flooding Simulation tool. A new robust and faster time-domain calculation method for prediction of progressive flooding has been developed in Task 3.1 of the FLOODSTAND project, *Ruponen et al. (2011)*. In order to achieve reliable predictions of the intermediate stages, the breach size and location need to be determined with sufficient accuracy. Thus reliable and well-placed water level sensors are required. If the flooding is not analysed in time-domain, the flooding sensors could be simpler i.e. on/off switch however there are many practical reasons why level sensor are still preferred, even if no time-domain analyses are required. One key issue with on/off switches is that they require the flooding detection system to keep track of events in the pasts. In practise no system manufacturer has been able to make a flooding detection system, which could accurately determine the origin of the flooding, using on/off switches. This is a strong argument against using on/off switches in flooding detection.

First, the typical sensor types and calculation techniques are briefly presented and then some requirements are established. The basis for this work is the flooding prediction tool, developed in Task 3.1 of the FLOODSTAND project, *Ruponen et al. (2011)*.

Finally guidelines for sensor placement in typical compartment layouts of passenger ships are presented. The two sample ship designs, developed in Task 1.1, *Kujanpää and Routi (2009)* and *Luhmann (2009)* are used as examples.

3 MEASURING FLOODWATER PROGRESSION

3.1 Flooding and Sea State

While the ship is breached, the flooding rate of the incoming floodwater can be affected by the outside sea state, the resulting ship motions and possible sloshing inside the ship. Rognebakke in his doctoral thesis, *Rognebakke (2002)*, describes sloshing as violent resonant free surface flow. The floodwater inside the ship has a significant damping effect and the sloshing of liquid in rooms is likely to decrease possible resonance with periodical waves *Rognebakke (2002)*.

It is clear that in floodwater measurements filtering is required. Required filtering requires knowledge on what values the system is trying to derive, and therefore raw output is expected from the sensors. When the signal is filtered, the information which remains depends on the filter length. If we want to ignore possible sloshing effects inside the ship the filter length should exceed the natural roll period of the ship. For a passenger ship with a typical metacentric height GM of around 2 meters, the expected natural roll period is between 15 to 30 seconds. To eliminate any sloshing or phase difference between level and floating position measurements[1], the filter length should always exceed these periodical motions of the ship – heave or roll – whichever has the longest period. The wave period should also be considered, however this is likely to be less than the ship's natural roll frequency. Also the pitching motion should be covered by the filter.

Figure 1 displays the results from measurements by *Akyildiz and Ünal (2004)*. A tank, which measured 92 x 46 x 62 [cm], was filled 25 %, and as it was forced to turn from one side to another with a constant period, the pressure was measured at 6 cm from the bottom. The tank had various bafflers, which could be removed or installed. Pressure and level are considered linearly proportional.

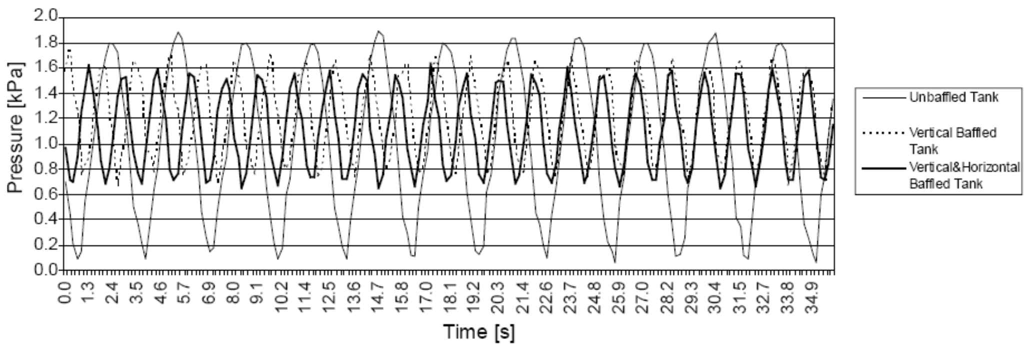

Figure 1: Changing pressure values for the roll frequency = 2.0 rad/s, pitch angle 8º

Figure 1 shows the effects of the sloshing in the tank as changing pressure at the sensor near the bottom corner of the tank. The clear period of the pressure oscillation arises from the induced pitching motion. Results for a random motion were not studied in *Akyildiz and Ünal (2004)*. At first it seems, that simply by applying long enough filters, the effects of sloshing could be entirely removed from the level/pressure measurement.

3.2 Flooding Detection Sensors

Until SOLAS was amended with Reg.II-1/22-1 (Entered into force 1 July 2010) the cruise line industry has been following guidelines in MSC 77/4/1 with varying applicability, and in general ships have too few sensors compared to the recommendations of this study.

MSC.1/Circ.1291dated 9 Dec 2008 provides guidance for the flooding detection systems for watertight spaces below the bulkhead deck, required by SOLAS regulation II-1/22-1 for passenger ships carrying 36 or more persons and constructed on or after 1 July 2010.

[1] If level is corrected by trim and list, the measurements have to be in sync. This may not be the case, if the changes in either trim or heel are rapid compared to the measurement frequency of level.

The terminology used in the document defines "sensor" as a device fitted at the location being monitored that activates a signal to identify the presence of water at the location. This definition covers every device capable of detecting water but does not require capability to evaluate the amount of it. In the following chapters "sensor" means a level sensor and devices capable of detection only are separately addressed.

3.3 Use of On/Off Switches in Flooding Detection

The simplest flooding detection sensor is an on/off switch. However, it can only indicate whether the location of the switch is flooded or not. There are currently no good models on how to use on/off switches with flooding detection or prediction. In practice level sensors are much more suitable for this task and on/off switches are never recommended.

On/off switches do not allow flooding rate to be measured. And even though it is possible to make flooding predictions without accurate flooding rates, the accuracy of such predictions would not be good. Another problem is how to estimate the amount of liquid there is inside the ship and how it affects the ship's stability.

The use of on/off switches can be used mostly only in double bottom voids or in other similar spaces without any possibility to progressive flooding and where possible floodwater amounts are small. It should be noted however that detection of flooding is the first priority, and on/off switches may be acceptable in some cases where level sensors cannot be used.

3.4 Level Sensors

Time domain flooding simulation and prediction requires continuous real time level indication from the flooded spaces in order to define the volume and flooding rate at each time.

Electric pressure sensors with the sensor element located inside the tank are the most commonly used sensors for measuring the contents of ballast water and consumable liquid tanks on board passenger ships and ferries. The sensors are widely regarded unreliable both in way of reliability and measurement accuracy. Because of the fact that the tank contents are constantly monitored by the crew, the malfunctions of the sensors are, however, easily detected.

The suitability of electric sensors for dry space monitoring is questionable. The sensors stay dry for years but must work when the room is flooded. Checking of the condition of the sensor is difficult since the sensor element needs to be exposed to a known pressure in order to verify the result.

The electro pneumatic sensor system has in practice proven to be the only reliable and accurate enough system for dry space monitoring. It is therefore the only system considered in the study.

3.5 Electro Pneumatic Level Sensors

Flooding sensors in dry spaces may stay unused for the whole lifetime of the ship and they still have to remain operational at all times. Every year more and more passenger ships are being equipped with flood detection systems based on pressure measurements of air flowing in pipes. Companies like Emerson Process Management and MTM (Marine Tank Management) manufacture suitable sensors that can be used in tanks or in dry spaces. The operation principle is almost the same for both manufacturers and the measurement principles are explained for Emerson's LevelDatic system.

It should be noted that the reference to a particular manufacturer is only for illustration of the measurement technique (measuring pressure at a specific point in a room), which ultimately determines the maximum achievable measurement accuracy. Focusing on one particular model or manufacturer does not limit the analysis, but serves as an example of the problems related to measuring liquid surface level.

In the following text describing electro pneumatic level sensors, the position of the actual *pressure sensor* (in a cabinet) and the measurement point are different. For simplicity the word *sensor* refers to the end of the air pipe.

In LevelDatic systems, the pressure is measured at a cabinet, connected to a pipe, which leads to the observed space or to a tank. Air is being supplied to the pipe in a steady flow (about 0.5 l/min for floodable spaces), which keeps the pipe constantly filled with air. The air pressure in the pipe is constant along the pipe and therefore the pressure at both ends of the pipe is the same as the hydrostatic pressure at height H_0 (See Figure 4). The pressure at the end of the pipe is the same as in the cabinet and. This technique allows the actual sensor to be placed in a safe place inside the cabinet, where it is protected from mechanical stress and water. The viscous effects of air flowing through the pipe should be corrected by calibration and this is a demand for constant flow systems. Furthermore a flow controller is needed to keep the air flow as constant as possible.

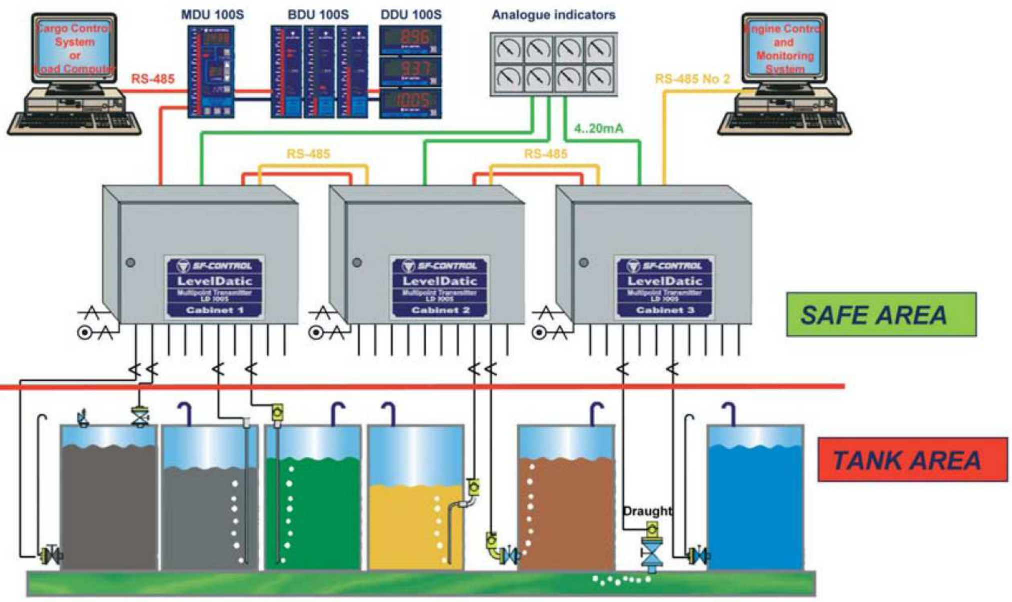

Figure 2: LevelDatic Instrumentation

Figure 2 illustrates a typical LevelDatic instrumentation arrangement. Several tanks and dry spaces are connected to the closest cabinets usually without crossing fire zone limits, but other arrangements also exist. The cabinets are usually placed on the bulkhead deck and contain the actual pressure sensors. The pipes leading to the dry spaces have no active components that might become inoperable. The air pipes shown in Figure 2 are usually 5 to 30 meters long and their inner diameter is between 5 mm to 10 mm, but there is no theoretical limit from measuring point of view.

A test valve should be installed that allows checking the pipe. The air flows constantly from the cabinet to the dry space and, if the pipe is blocked, the pressure will increase and induce an alarm or notification on higher level of the flooding detection system i.e. bridge panel. If the pipe is cut, the pressure will not increase and test can also detect broken pipe. Figure 3 shows the measurement instruments in the cabinets more closely.

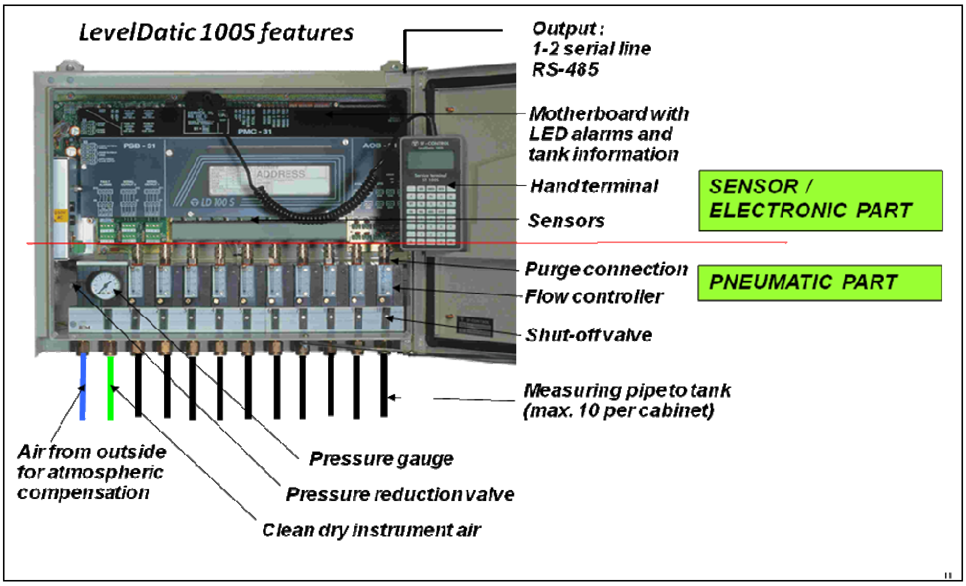

Figure 3: LevelDatic cabinet

The following equation is used by the LevelDatic system to convert measured pressure at the cabinet to corresponding level in meters:

$$H = \frac{P_{ABS} - P_{REF}}{\rho g} + H_0 \tag{1}$$

where P_{ABS} is the measured pressure compared to P_{REF}, which is the atmospheric or other reference pressure. The difference is corrected by the flow resistance in the measuring line P_J and the resulting hydrostatic pressure is converted to corresponding level using the density ρ and specific gravity g. See Figure 4.

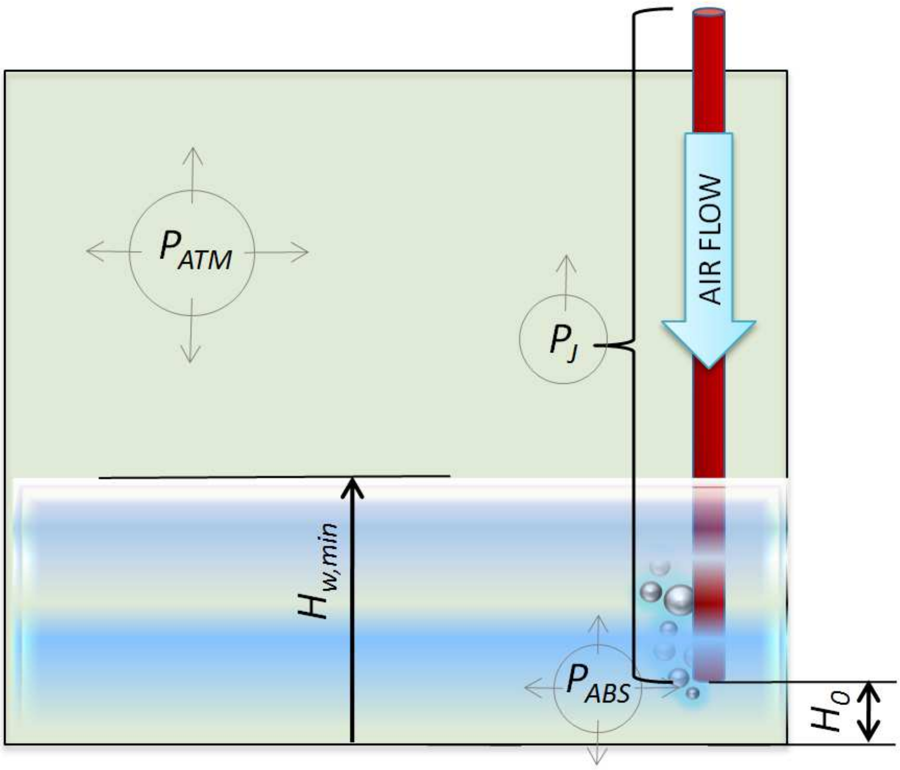

Figure 4: Illustration of measurement quantities

The height H_0 (usually the height of the pipe end from the floor) is the so called sensor height. Naturally any water below H_0 will not be detected, so the pipe ends should therefore be as close to the lowest point of the room as possible. Heights like 0.1 m and 0.5 m have been proposed by different sources as the default height. The origin of these values may be from tank measuring analogy, where there might be mud in the bottom etc. This is not the case in machinery or accommodation spaces and the sensors can be placed in those spaces very close to the floor. IMO MSC,1/Circ.1291 finally concludes in section 8 that the vertical location of the sensor should be as low as practical in the watertight space. If the sensor is placed too low it might create problems for maintenance and testing depending on the sensor type.

There is also another practical problem related to the height at which the sensor is placed and to this particular sensor type. The measurement signal may contain random noise and variations from pressure i.e. ventilation system and experience has shown that some threshold-limit for alarm is required so that flooding detection system does not interpret these pressure variations as actual flooding. This limit is called alarm-limit. Usually the alarm-limit is approximately 0.1 m or more but also higher values, like 0.5m have been used in special cases. Having false alarms from flooding sensors is currently still common. These undermine the importance and reliability to such a degree that it can be asked whether such system is useful in real life cases.

It should be noted that this alarm-limit is added to the reference height H_0. This means that if the sensor is placed so that H_0 is 0.1, with safety range of 0.1m the actual height where flooding is detected is 0.2m. So system will in effect wait for water to rise above 0.2 m before alarm is sounded. These values are slightly exaggerated to illustrate the link between a high alarm-limit and detection time. On/off switches share the alarm-limit problem if they are based on measuring pressure.

3.6 Error Estimation of Calculated Volume with Variations in the Measured Pressure

Measurement result contains always some noise. When liquid volume is measured from the pressure the accuracy of the volume depends on the variations in the obtained pressure data/signal. If the volume is disturbed its free surface oscillates in a complex array of waves travelling in different directions with varying wavelengths. If there’s no breach, or the time between measurements is very short the volume does not change, so if we measure the pressure that contains some random oscillation, then surely we need not say that the accuracy of the volume measurement is directly in proportion to any random peak disturbances. Before we calculate the accuracy of the measured volume, we must first filter the signal to get the mean “undisturbed” values.

If the measured pressure (or level) contains some variation (sloshing etc.), question is raised how much is the mean error of the measurement? When floodwater is rushing into the ship, the flow causes disturbances on the surface and on the pressure, and the liquid may start sloshing. The disturbances of the surface appear as variations in the measured pressure and these variations are either random or periodic and can be filtered out from the signal, for example, by averaging over time T_f, which in this text is referred to as the filter time. The variations tend to increase or decrease as the level changes. For example: at first, as the room starts to flood, the liquid motion is dominated by viscous forces, because the liquid thickness is small relative to volume. But if the water rises some more, the liquid is allowed to move more freely. At higher filling percentages the motions are dampened by the ceiling. Any disturbances caused by the flow from an opening are likely to be damped as the floodwater level rises. So we might make a reasonable assumption that early measurements of the flooding contain more errors than the later more “stable” measurements.

If we suppose that the surface of the floodwater is flat and parallel to sea level, the volume of the floodwater depends only on the floor area (room geometry) and the liquid level. If we assume also that the room geometry does not change, so that only the free surface moves, then if the level is measured at the floor level, the relative variations have a tendency to weaken as the level rises. This is because the disturbances at the surface diffuse into the liquid volume and the liquid acts like a filter itself; taking the energy of the motion and transforming it into heat by friction; consider for example the sea bed, which can be calm while a storm is raging at the surface level. If the flooding rate is positive and the room is filling, the measured level is again expected to be more accurate as the volume increases; that is if the volume does not reach some resonant mode and start sloshing violently.

If we want to know the volume of the floodwater in a room, we should first filter out the random fluctuations from the pressure/level signal. If the variations in the signal contain several frequencies, which frequencies should be filtered out before the mean variance is calculated? If the sensor is randomly hit by small and rapid waves, which are not caused by the flow from the breach itself, but rather by water sloshing with the ship’s motion, then the frequency of these disturbances depends in some way on the ship’s rolling, yawing or pitching frequency. Therefore the motions of the floodwater in a room and the measured pressure oscillations are connected to the wave periods of the outside sea. If the trim and list of the vessel are measured, the minimum filter length can be determined from the frequencies found in the ship’s motions in, for instance, the roll period.

If a ship is rolling and pitching with an average period around 20 seconds, any frequencies above 1/20 Hz should be filtered. Level sensors are capable of transmitting measured level with a frequency of around 1/5 Hz. On existing installations with level sensors and NAPA interface connections, a value is typically read from each sensor once in every 5 to 10 seconds or more frequently. If the low pass filter is set to 1/20 Hz, this would mean two measurement points per filter length. This may be too few for any filter to work properly. So either the filter length should be prolonged or the measurement frequency increased. Once a suitable filtering is found, the mean variance of the measurement can be calculated and converted to mean variance. In calm circumstances the liquid level height can actually be measured quite accurately; even within a few millimeters. In less calm circumstances we can always apply some filtering and we ought to be able to convert the level measurements to rather high precision liquid volume readings in most cases.

4 REQUIREMENTS FOR DECISION SUPPORT SYSTEM FOR FLOODING

4.1 Decision Support for Flooding

A Decision Support system must be able to make calculation regarding the current and future stability of the ship. This requires that either the damage extent is known in detail or there is some reliable information about the breach, where floodwater is entering the ship.

4.2 Assessment of Damage Size and Location

If floodwater levels in all flooded rooms and trim and list are recorded, it is possible to use an inverse method to determine breach size and location. The accuracy of the estimated location and size are in proportion to the number of measurement points and the variances in the measurement. There are other factors that interfere and some cases inverse method can produce several equivalent solutions. These are not critical from the standpoint of predictions unless the breach is situated very close to the water level.

4.3 Case Study on Sensor Placement (ICCGS'2010)

4.3.1 Background

In the early phase of the FLOODSTAND project an initial study on breach detection was performed. This is reported in detail by *Penttilä and Ruponen (2010)*. In that study several damage cases were analyzed. Each case which resulted in flooded was calculated and from the calculation results the breach size and location were solved. If the breach can be solved from floodwater measurement, it is then possible to make predictions how the flooding will progress. Therefore if the breach can be solved, the flooding detection system i.e. sensor arrangement is good enough for prediction purposes.

Since then both the breach detection and flooding prediction analysis methods have been further developed (Deliverable D3.1, *Ruponen et al., 2011*) but the main observations on the sensor density and noise in the measurement signals are still considered to be valid. Therefore, the main findings of this initial study are summarized in the following.

4.3.2 Studied Ship and Damage Cases

The studied large modern passenger ship has 19 watertight compartments extending to the bulkhead deck. The NAPA-model has a total of 312 openings, which connect 170 rooms. Definition of a room is that it is always watertight and water can only spread to other rooms only through openings. An example of the 3D model with rooms and openings is presented in Figure 5. Main dimensions of the ship are listed in Table 1.

Table 1: Case study ship data

Gross tonnage	90 000
Length over all	290 m
Breadth	32 m
Draft	7.7 m
Initial GM	2.0 m

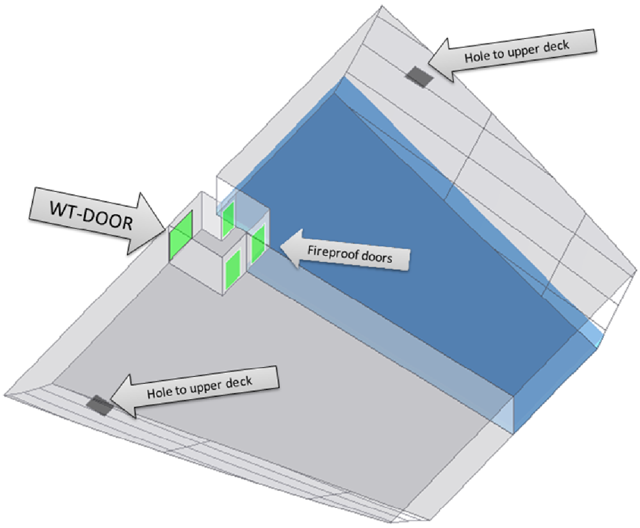

Figure 5: Example of the 3D model and level of detail during flooding

The aim of this study was to find out whether an inverse method could be used to determine the breach size and location and also how the sensor arrangement affects the results.

A set of 433 damage cases were generated by Monte Carlo simulation on the basis of damage statistics[2] for collisions. However, cases with high penetration/length ratio were ignored since in those damage cases the colliding ship is likely to have a notable effect on the flooding through the breach. Each damage case was limited to a single breached room and the area of the breach was limited between 0.01 – 2.0 m^2. The limitation was necessary due to current measurement capabilities. If the breach was very large, the damaged compartments would fill with such speed that neither the selected time step for simulation nor a real flooding sensor would be able to measure the flooding rate. The applicability of the simple inverse method for very large breaches i.e. several breached compartments is not included in this study. However, in general it is considered that the damage location is easier to detect if the damage extent is large because the probability that the flooding is detected by a sensor is increased.

Each damage case was calculated using the NAPA Flooding Simulation tool, assuming a calm sea state. Total of 225 cases were calculated with all doors closed and 208 cases were calculated with all fireproof doors (total of 167) open. Most cases resulted in progressive flooding through various openings in the ship. On average 2.3 rooms were flooded during the simulation time (120 s) when all fireproof doors were closed and an average 2.7 rooms were flooded when the fireproof doors were open. All watertight openings were always defined as closed.

After each case was simulated the results were stripped in order to make the comparison for an authentic case. All data which would not be available in a real situation was removed. The available data after the stripping consists of the floating position and floodwater levels in the rooms with sensors as functions of time (in NAPA table format). The entire process of testing the inverse method is illustrated in Figure 6.

[2] As in SOLAS2009

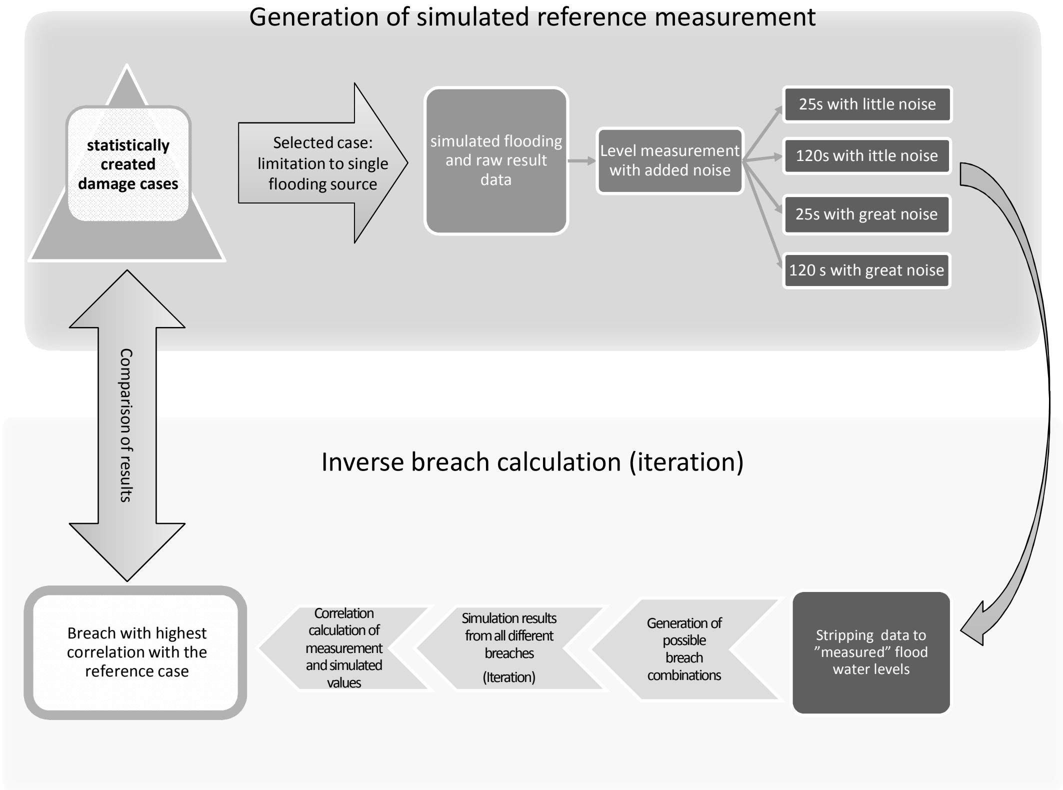

Figure 6: Process diagram illustrating the method of testing the inverse method

4.3.3 Added Noise in Reference Results

A true measurement always contains some measurement errors or noise. In this study two different amounts of random noise were added to the reference data. The two graphs in Figure 7 illustrate the added noise to the measurement of 4 flooded rooms.

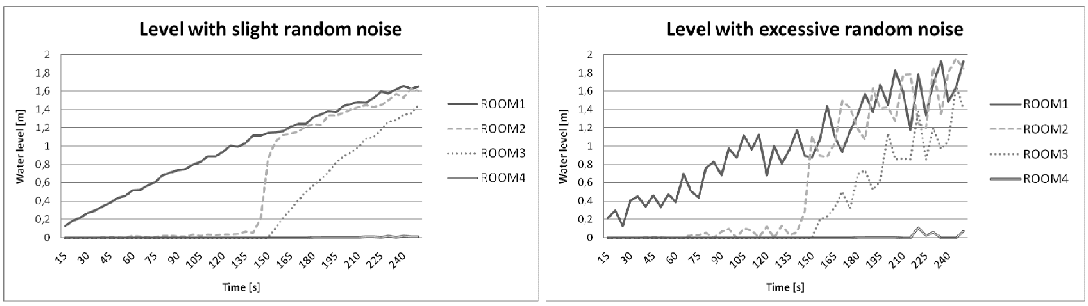

Figure 7: Level with slight added noise (left) and with excessive added noise (right)

The purpose of the generated random noise was to simulate disturbances in the floodwater level measurements. The added noise makes it more difficult to calculate the initial flooding rate and the origin of the breach and makes the case more realistic. However, it should be noted that the added noise does not correspond to disturbances due to sloshing and is only an approximation of random measurement distubances. Typical flooding sensors described in chapter 3 may also react to changes in air pressure due to flooding, but this effect is not studied in this text. All flooded spaces are assumed to be freely ventilated. The added noise is expected to decrease the likehood of determining the correct breach succesfully.

4.3.4 Sensor Arrangement

The ship is equipped with 57 flooding sensors in total of 245 rooms/tanks. 170 rooms are subject to progressive flooding and remaining 75 are closed and not connected to any other rooms by openings. There are 45 flooding sensors in the 170 rooms. The “density” of the sensor arrangement in potential areas of progressive flooding is calculated by

$$\rho_{sensors} = \frac{n_{sensors}}{n_{connected\_rooms}} \tag{2}$$

In this case the density of the sensor arrangement is approximately 0.26.

The calculations were performed for two sensor arrangements. All cases were calculated first with the assumption that all rooms are equipped with a sensor (sensor density 1.0) and then with the sensor density 0.26. When each room is equipped with a sensor the success rate of calculating the correct breach is expected to be 100% and less for the case where only selected rooms are equipped with a flooding sensor.

In the case of a sparse sensor density (0.26), noise levels of 2% and 10% were considered realistic and were used in the calculation. But in the case of the high sensor density (1.0) noise levels were 5% and 35%. The higher noise levels were used because solving a breach with a very tight sensor arrangement is almost a trivial task. Therefore excessive noise was added in order to really test the method.

4.3.5 Results

A summary of the damage cases is presented in Table 2. Some of the generated damages resulted in too small a breach compared to the distance from the waterline. These damages did not result in noticeable floodwater amounts and a total of 131 (70 + 61) cases were left out from the inverse calculations because of this. It should be noted that with longer filter lengths also these damages should have been included. These cases could also be described as *creeping* flooding as well as some cases where flooding was not detected at all. There were a total of 33 (22 + 11) *unnoticed* flooding cases. It is not known whether floodwater would have spread to rooms with flooding sensors if the time span had been longer. The final number of suitable cases for the inverse calculation was 299. Table 2 lists the cases in more detail.

Table 2: Summary of generated damage cases

	All doors closed	***Fireproof doors open***
Total number of generated damage cases	235	228
Flooding not detected by flooding sensors	11	22
Breach too small (no noticeable flooding)	70	61
Total number of remaining suitable damage cases	154	145
Average breach size	0.21 m^2	0.21 m^2
Average distance from waterline	0.98 m	1.17 m
Average num. of flooded rooms (within 120 s)	2.3	2.7

The success rate of the inverse method was measured by checking whether the method was able to determine the correct damaged room (breach location) from detected floodwater and whether the calculated breach area corresponds to the reference case within a ±30% margin. The general arrangement and the sensor arrangement of the ship model were such that in 65% of the cases the floodwater was detected by a flooding sensor in the primarily flooded room.

Table 3 shows the results of the study for all 299 inversely calculated cases with the assumption that all rooms are equipped with a flooding sensor and Table 4 shows the results with a typical sensor arrangement of sensor density 0.26.

Table 3 shows that the method used in this study is very likely to find the correct location for the breach even with high amounts of noise in the measurement data as long as each room is equipped with a sensor. The average success rate in finding the primarily flooded room was 98.6%. This is slightly less than the expected success rate of 100%. The success rate of calculating the correct breach area within the margin was more dependent on the filter length and noise than the success rate on locating the breach correctly.

Table 3: Success rate of calculating the correct breach with sensor density 1

	All doors closed		***Fireproof doors open***	
	Location	Area	Location	Area
Filter 120s				
Noise 5%	99.6 %	60.7%	99.0 %	61.1%
Noise 35%	97.3 %	21.9%	98.1 %	25.0%
Filter 25s				
Noise 5%	100.0 %	68.0%	98.6 %	64.4%
Noise 35%	97.8 %	37.7%	98.1 %	41.1%

Table 4: Success rate of calculating the correct breach with a sensor density 0.26

	All doors closed		***Fireproof doors open***	
	Location	Area	Location	Area
Filter 120s				
Noise 2%	69.5%	64.5%	76.6%	65.8%
Noise 10%	67.5%	56.7%	74.5%	41.7%
Filter 25s				
Noise 2%	67.5%	31.7%	74.5%	41.7%
Noise 10%	68.2%	20.1%	70.3%	28.4%

Table 4 shows that the same method, when used for a sparse sensor arrangement, is less likely to find the correct breach. The average success rate in determining the primarily damaged room was 71.1%. Again the effect of noise and filter length is more noticeable for the calculation of the breach area than the location. It should be noted that the two result sets were calculated with different amounts of noise and are not directly comparable. Naturally the opening status of the fireproof doors has a greater impact on the results when the sensor arrangement is sparse. When all fireproof doors are open, the method was 8.5% more likely to determine the breach correctly.

The target of this study was to find out whether it is possible to determine the location and size of a breach purely from flooding sensor output without human intervention. A total number of 2392 cases (299 cases with two different sensor arrangements and combinations of 2 different filter lengths and 2 different amounts of random noise) were calculated inversely and the results strongly indicate that the inverse method is applicable in determining the breach from the water level data only if the sensor arrangement is dense enough. When calculated with a typical sensor arrangement, the method was able to successfully determine the correct floodwater origin in 71.1% of the cases. However the method was only able to derive the correct breach size within a reasonable margin in 44% of the cases.

It should be noted that the effect of sensor height was not taken into account. This has most effect on the filter length, which loosely defined corresponds to time to react to flooding. The higher the sensor is, the longer the crew will have to wait before any notice or predictions are available. In some cases a sensor placed too high can allow water to creep to the next room unnoticed, and therefore it is expected that the inverse method would be more likely to fail if the sensors are not placed low enough. Alarm-limit has no effect on the inverse method, because inverse method is designed to use raw unfiltered data.

5 GUIDELINES FOR SENSOR PLACEMENT AND TECHNICAL REQUIREMENTS

5.1 Introduction

This chapter will outline the guidelines for sensor placement and technical requirements for flooding detection under bulkhead deck. In general the guidelines propose that all significant spaces in a ship are equipped with floodwater level measurement sensors. Sensors must be fault tolerant and installed so that dangerous flooding is always detected at an early stage.

SOLAS regulation II-1/22-1 requires passenger ships carrying 36 or more persons constructed on or after 1 July 2010 to be provided with flooding detection systems in watertight spaces below the bulkhead deck, based on guidelines developed by IMO. The following guidelines for flooding detection sensors is supplementary to IMO MSC.1/Circ.1291.

These guidelines are intended to provide more detailed requirements for flooding detection systems to provide information in the case of flooding in order to assess the actual flooding situation and to support the decision-making process.

The following definitions are used:

- **Flooding detection system** means a system of sensors and alarms that detect and warn of water ingress into watertight spaces. Continuous flood level monitoring may be provided, but is not required.

- **Sensor** means a device fitted at the location being monitored that activates a signal to identify the presence of water at the location. In the following text, however, sensor means a level sensor. Possibility to use on/off switches is specifically mentioned.

- **Alarm** means an audible and visual signal which announces a flooding condition requiring attention.

5.2 Guidelines for Sensor Locations

1) Flooding detection sensor should be placed so that floodwater is always detected before stability of the ship is compromised.
Comment: Suitable stability criteria are not available but are suggested for as future work

2) Each watertight compartment should have two level sensors on each deck below bulkhead deck, including double bottom. In narrow compartments e.g. forward areas it is sufficient to have only one sensor per deck
Comment: this is based on redundancy but main reason is detecting flooding with large heeling angels

3) In large or complex spaces e.g. car deck on Roro Passenger ships, significant amount of floodwater may accumulate before floodwater reaches a sensor. In such spaces, the number of sensors and their location should be carefully considered to ensure that the stability of the ship is not compromised before flooding is detected

4) Spaces which are surrounded by non-watertight boundaries, but where it is expected that the structure will affect the flooding progression, should at least have one sensor.

5) Ships which are vulnerable to flooding above bulkhead deck should also have flooding detection in those compartments. The same principles as for sensor location below bulkhead deck should generally be applied.
Comment: Sensors above bulkhead deck should detect flooding progressing to other compartments below bulkhead deck and flooding progressing past a partial bulkhead

Comment: mainly for evaluating how much water is above bulkhead deck (not required for predictions).
Comment: If there is need to minimize the number of level sensors, it is better to reduce sensors from the higher decks. If down-flooding arrangements allow instantaneous flooding to lower deck and vice versa with all angles of heel, having a sensor on the upper deck is not critical

6) Sensors should be placed to the aft side of a room, if the room is situated aft of mid ship and forward side of the room if the room is situated forward of mid ship.
Comment: The ship is likely to trim to the direction of the flooded compartment

7) Sensors on higher decks are to be placed near to an access to lower decks (close to stair cases, down flooding ducts or non-watertight escape routes)
Comment: water is likely detected near the place where it may progress to other rooms or decks. These places require a sensor that can detect very low floodwater levels

8) Sensor including cabling/piping should be located transversally so that they are protected from minor collision and bottom damages. The sensor cabling should generally be routed inboard and upward before carried through transverse watertight bulkheads, and then as close to the centerline as practicable
Comment: in case of bottom damages electro pneumatic sensor are considered most reliable, since the actual sensor will not be damaged.

5.3 Guidelines for Sensor Requirements

9) Each sensor should always be placed as close to the lowest point of the room as practicable
Comment: especially on higher decks where water does not accumulate but tends to flow to lower decks, consider using sensors that have very low alarm-limit;
Comment: creeping of floodwater past a sensor to adjacent compartment can depend e.g. on the height of doorstep.

10) Each watertight space and tank below bulkhead deck and bounded by the ship's hull should have at least one flooding sensor, depending on the width and volume of the space.
Comment: even smallest rooms in double bottom require a flooding sensor

11) On/off switches may only be installed to small spaces (i.e. sealed compartments in double bottom) from which the flooding cannot progress to other spaces.
Comment: Applies to relatively small rooms from which the flooding cannot progress to other rooms etc.
Comment: The smallest rooms e.g. less (IMO 30m^3 or 1 cm immersion) 0.5 % from displacement do not necessarily require any sensor, because the effect on stability is insignificant and damage is most likely detect in other rooms already (in volume or free surface effect on ship's stability). However, at least one on/off switch (sensor) is required in the double bottom (largest room) in each compartment

12) Sensors / measurement points should be placed so that they are visible and easily accessible for maintenance, check and testing.

13) Flood level sensors should have trim & list correction

14) All sensors / measurement points should be labelled clearly as parts of flooding detection system

15) There should be a possibility to test an individual sensor easily as part of a routine task

16) Flooding detection system should be designed so that if any part of the system fails i.e. sensor error, the ship's crew is notified.

17) Flooding detection system and functionality of each sensor and resulting alarm should be verified periodically
Comment: It may be required that the sensor maker should prepare a maintenance/testing plan/manual. Drawing of the sensors location should be provided.

18) Sensors measurement variations and the alarm limits should be adjusted so that there are not false alarms.
Comment: repeated false alarms may cause the ship's crew to undermine the importance of the system
Comment: Raising the alarm limit, will also make the system slower or less inclined to detect flooding. Flooding detection capability should be ensured when adjusting alarm limits.

5.4 Examples

5.4.1 Cabin Areas

Crew cabins are often located below the bulkhead deck. The number of cabins on one deck in one watertight compartment can be notable. These structures will likely hinder the flow of floodwater. On the other hand, the results of the full-scale tests with B-class walls and joiner doors in Task 2.1 of the FLOODSTAND project showed that these structures leak significantly, even under small pressure head of floodwater. Thus it was concluded that the B-class structures can be ignored in flooding simulations.

A cabin area is usually rather symmetric, extending from side to side. The modelling of the so-called "transient asymmetric flooding of symmetric rooms", *Spouge (1986)*, the cabin area room can be divided by a "virtual longitudinal bulkhead". With this approach, it can be ensured that the ship will heel towards the damage. For most cases just one virtual bulkhead is considered to be enough. Openings in these bulkheads, representing the transverse corridors, are needed. An example of this modelling is illustrated in conjunction with sensor placement in Figure 8.

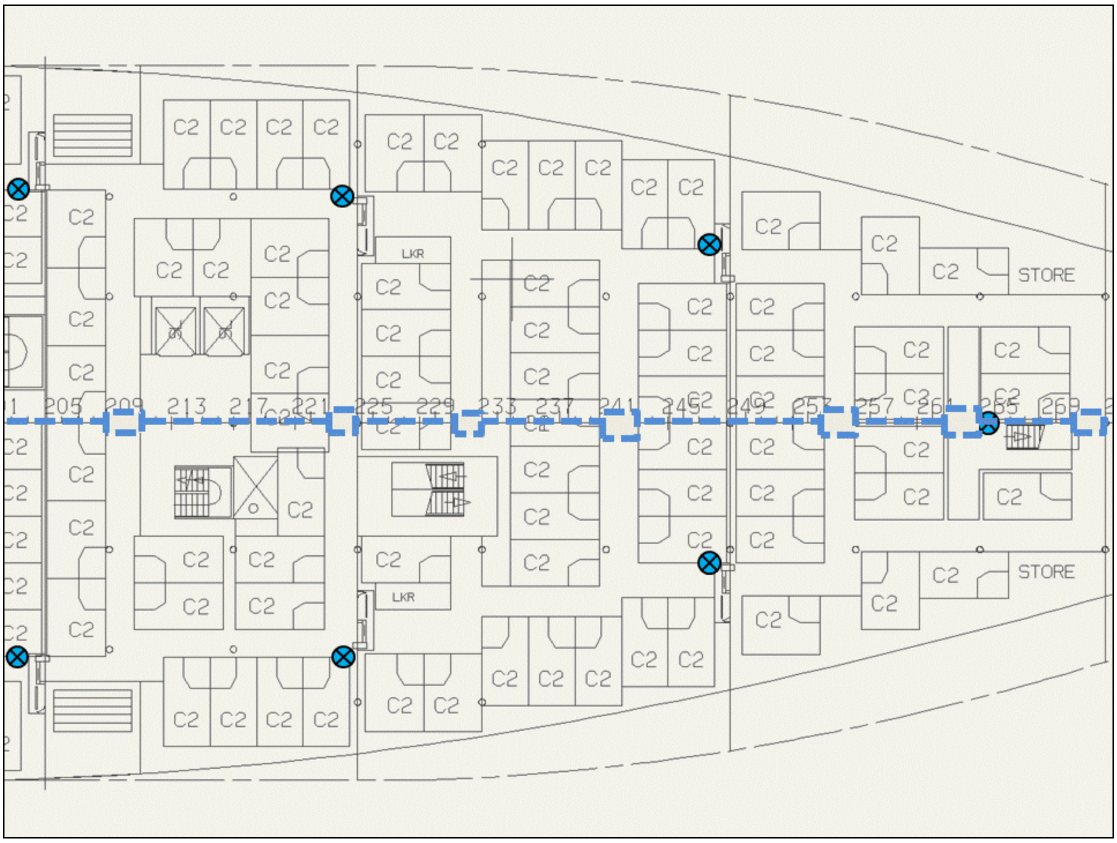

Figure 8: Sensors and virtual division in typical cabin area

5.4.2 Machinery Spaces

Some examples of sensor placement in machinery spaces are illustrated in Figure 9 and Figure 10. In principle, two sensors are needed for each space. The transverse location is selected so that the risk of damage to the sensor in the event of a collision would be as minimal as possible.

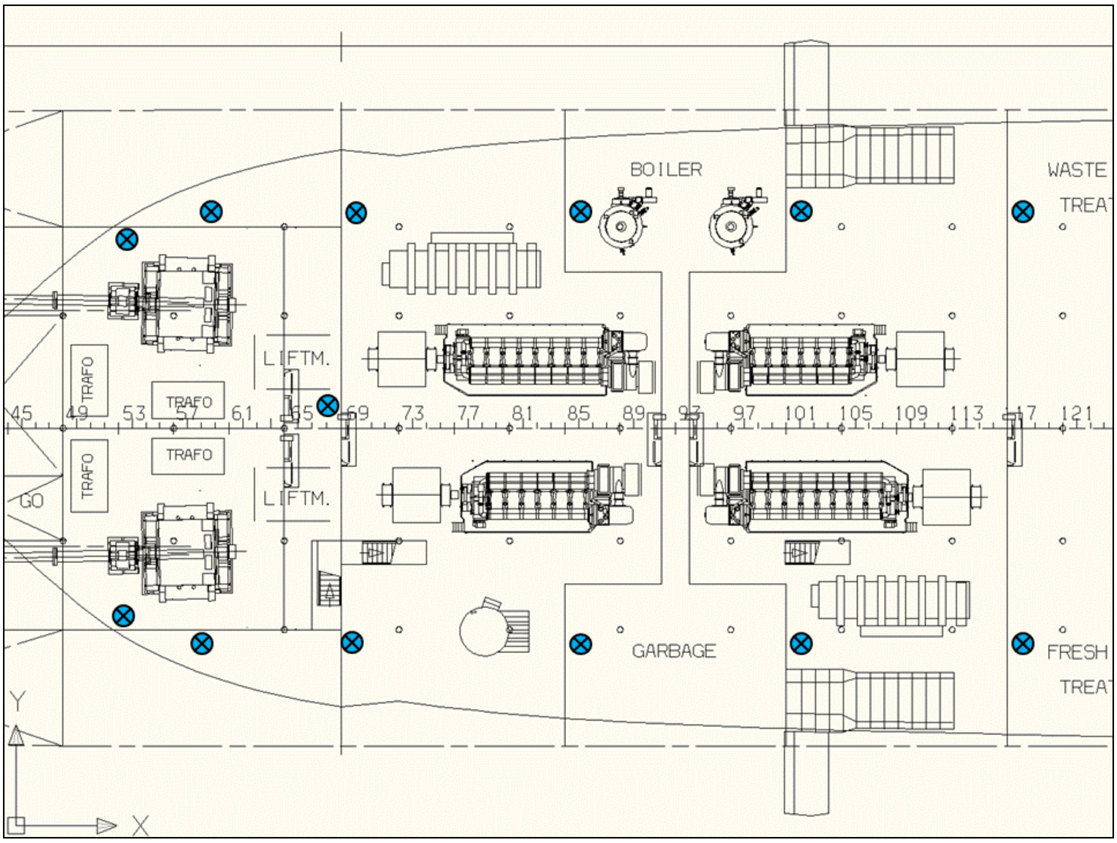

Figure 9: Sensors in machinery spaces

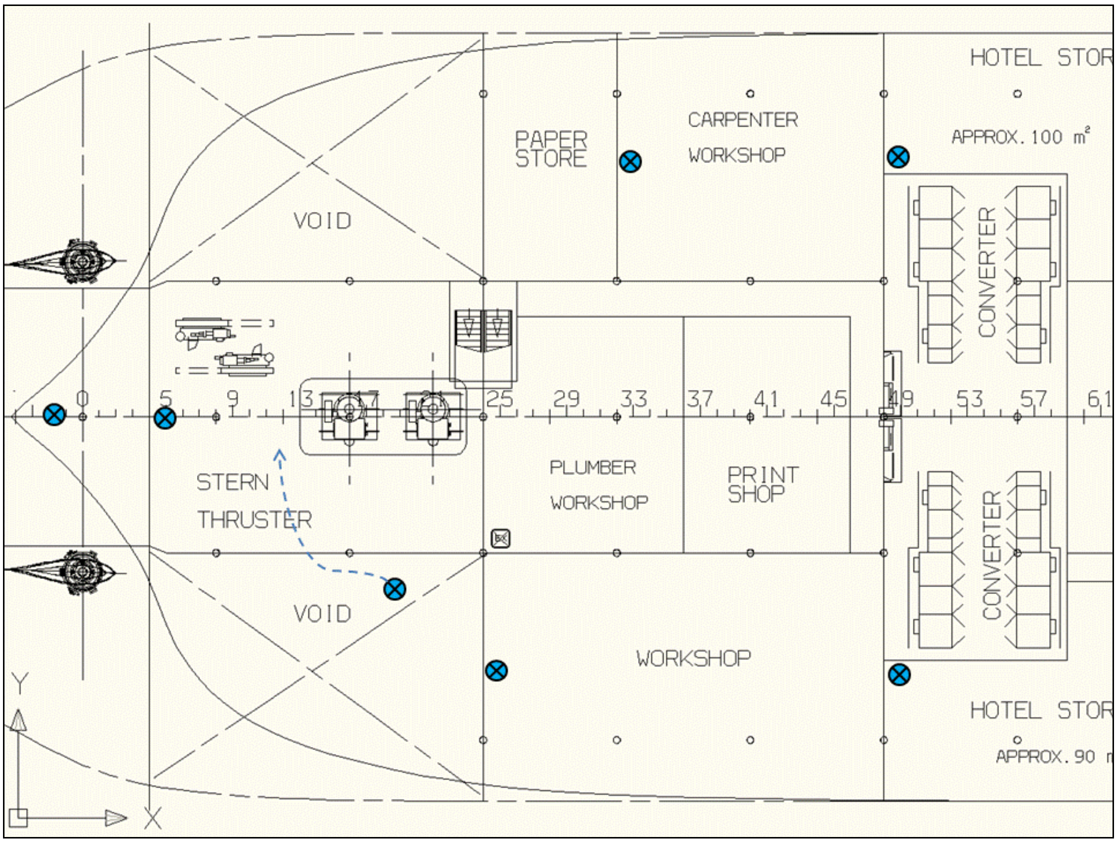

Figure 10: Sensors in machinery spaces

5.4.3 Stores and Laundry

These compartments may contain longitudinal A-class bulkheads, thus two level sensors are needed in order to achieve fast flooding detection. Some examples are illustrated in Figure 11,

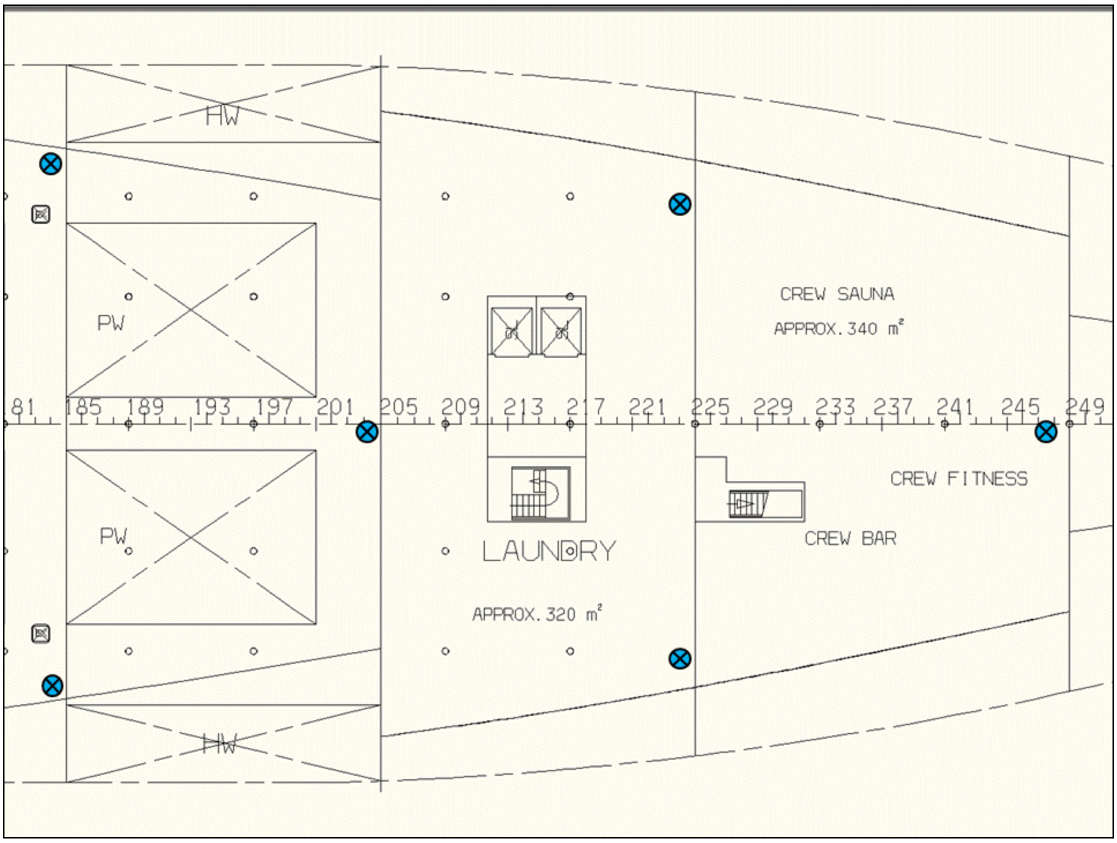

Figure 11: Sensors in laundry and linen store, separated by A-class longitudinal bulkhead

5.4.4 Bulkhead Deck

As mentioned in paragraph 5) in section 5.2, flooding detection may be needed on the bulkhead as well. Some examples are presented in Figure 12.

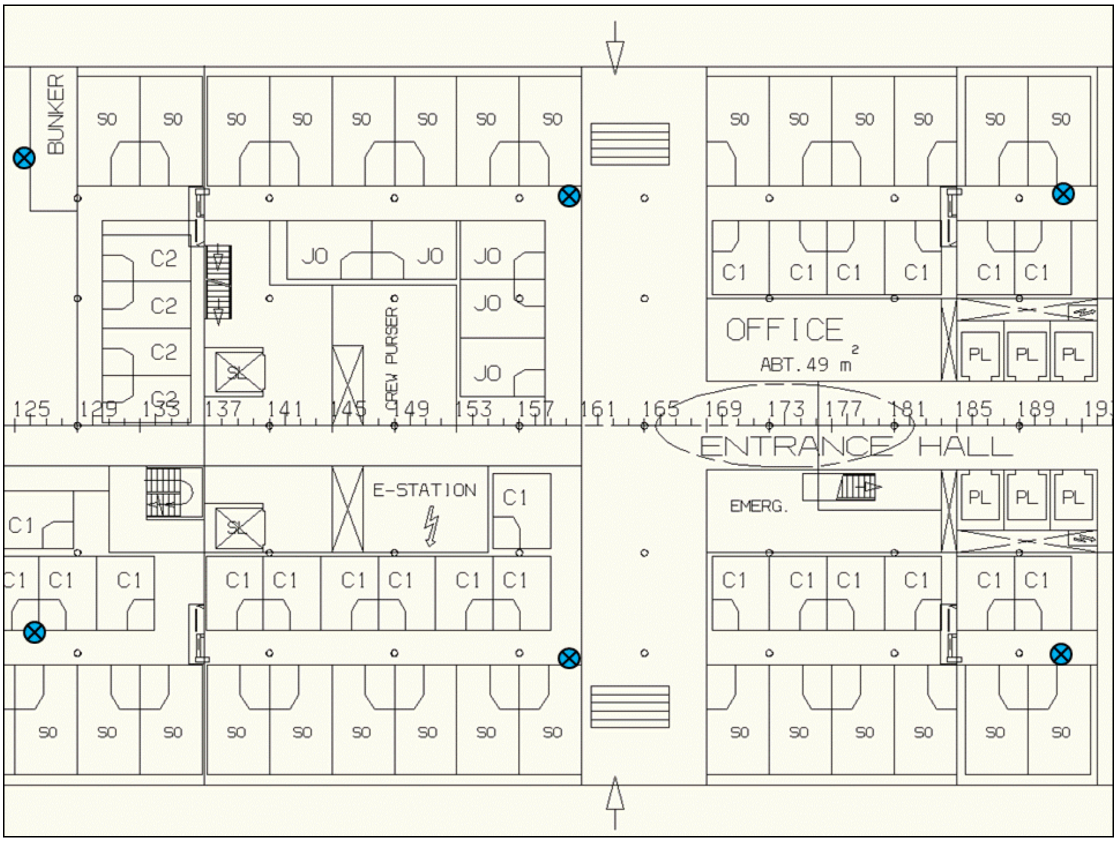

Figure 12: Sensors above bulkhead deck

6 CONCLUSIONS

Current guidelines for flooding detection are based on only *detecting* flooding not to make any further analysis. Requirements for floodwater sensors are higher when the real stability of the ship is calculated or predicted. There are good and robust methods of simulating progressive flooding in time-domain, but current guidelines are not describing where to place flooding sensors and what type they should be so that the methods could be used.

Decision Support systems set higher standards for flooding sensors but good sensor placement depends greatly on the general arrangement and the structures of the ship which have significant effect on progressive flooding like A-class structures. It is therefore essential that the ship specific arrangements are carefully considered in each case when the locations of sensors are determined. In chapter 5 (guidelines for sensor placement and technical requirements) some guidelines have been presented that, when applied, enable the use of more powerful Decision Support tools.

First principle used in the guidelines is that sensors should be placed so that the system can detect flooding before the stability of the ship is threatened. As parts of Decision Support system, sensor should detect flooding as early as possible. Second principle is that floodwater should be detected if it is significant. Third principle is that sensors should be placed so, that the system is able to determine where the breach is located.

Level sensors are necessary for obtaining the required data for flooding prediction onboard a damaged ship. In general there should be two level sensors on each deck in each compartment under bulkhead deck. This is much more than current standards. Also level sensor and Flooding Detection system should be adjusted so that there are no false alarms. Periodical checks for level sensors are also recommended.

Author recognizes that determining the state of the ship by floodwater measurements is not a trivial task and as a recommendation for further work it is suggested that suitable stability survival criteria that Master can use for evaluation of severity of flooding scenario should be developed.

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